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ARMSTRONG LABORATORY

USAF PHYSIOLOGICAL STUDIES OF PERSONAL MICROCLIMATE COOLING: A REVIEW

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Final Report for Period September 1980 - December 1992

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The voluntary, fully informed consent of the subjects used in this research was obtained as required by AFR 169-3.

The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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The U.S. Air Force has accomplished a number of research studies which evaluated the efficacy of selected personal cooling approaches for alleviating heat stress in personnel wearing certain protective clothing. Most of this work involved laboratory, as opposed to field, studies and incorporated human subjects performing work in either warm or hot environments. Both air and liquid microclimate cooling systems were evaluated. The general findings include: (1) personal microclimate cooling systems (both air and liquid) were shown to remove significant quantities of body heat, (2) in general, commercially available systems were inferior to in-house prototype units, (3) backpack (ambulatory) systems usage would likely have a limited user audience for a number of reasons, (4) some near-term; partial solutions to the problem may be at hand for selected deployments, and (5) microclimate cooling technologies on the horizon will likely not provide an optimum solution for most ground crew applications. The USAF Armstrong Laboratory has limited plans for further research in this area.

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LIST OF ACRONYMS AND ABBREVIATIONS

BDO	battle dress overgarment
CC	continuous cooling
CD	chemical defense
CDE	chemical defense ensemble
CW	chemical warfare
GCLCS	Ground Crew Liquid Cooling System
HR	heart rate
IC	intermittent cooling
IPE	individual protective equipment
LCG	liquid-cooled garment
MICS	Multiman Intermittent Cooling System
MOPP IV	Mission Oriented Protective Posture (Maximum Level)
NC	no cooling
SR	sweat rate
T_{bg}	black globe temperature
T_{db}	dry bulb temperature
T_{re}	rectal temperature
T_{sk}	skin temperature
$\bar{T}_{sk}$	mean skin temperature
T_{wb}	wet bulb temperature
WBGT	wet bulb globe temperature

USAF PHYSIOLOGICAL STUDIES OF PERSONAL MICROCLIMATE COOLING: A REVIEW

INTRODUCTION

Performance of many U.S. Air Force (USAF) mission-critical tasks requires personnel to sustain moderate-to-hard levels of work for extended periods. Performance of military operations within a chemical warfare (CW) threat environment imposes additional stressors that include both physiological and psychological factors related to the actual or potential exposure to chemical agents. For example, currently-available individual chemical protective equipment--the Chemical Defense Ensemble (CDE)--imposes specific burdens which can ultimately influence performance. Physical constraints of the CDE include reduced visibility, impaired communication, and diminished manual dexterity and mobility; these combined functional decrements can significantly affect task performance.

With respect to sustained work, however, the most important burden imposed by the CDE is the marked impediment of physiological thermoregulatory processes. The CDE consists of a heavyweight garment with low permeability, and impermeable mask, hood, boots, and gloves; it retards evaporation and significantly impedes heat transfer from the body. This constraint on heat dissipation is paramount in certain warm or hot climatic environments, while the effects of this constraint are greatly exacerbated as the work rate increases. In addition to the effect on task degradation and early exhaustion, wearing CDE while working at an increased metabolic rate can provoke heat stroke or death without medical or other intervention.

When all of these factors are considered together, it is easy to forecast a potentially disastrous situation for some troops wearing the CDE during sortie generation in airfield operations. It is this concern that has prompted the USAF and other branches of the armed forces to seek solutions to this thermal predicament. Notwithstanding workload, the environmental climatic status is probably the major factor in determining the severity of the problem; however, this condition is virtually uncontrollable. Prophylactic approaches that have been forwarded include: frequent rest periods; reduced workload; thermal acclimation; increased aerobic conditioning; a less thermally-burdening CDE; mass cooling areas; and personal cooling devices.

In the past, it has been the consensus that the last option--i.e., personal cooling systems incorporated into the CDE--may hold the greatest potential for real success in solving most of this problem. However, some researchers have begun to question the potential for full achievement of the goals using this strategy. This report will review the cooling problem with regard to past USAF work.

PHYSIOLOGICAL BACKGROUND

Humans, like many machines which perform work, oxidize fuel to obtain energy. However, biological machines do not convert the heat of oxidation into work; rather the body oxidizes food substrates at a relatively low temperature and converts this chemical energy into work and heat. Biological cells need this energy for certain "housekeeping" work such as the active transport of certain solutes across membranes. In concert with the first law of thermodynamics, all of this "internal work" eventually shows up as heat. Larger amounts of energy are needed when the body becomes physically active and performs "external work." Very large quantities of heat may then be produced. Even at rest, the body heat production is significant and important to the maintenance of physiological homeostasis.

Metabolic heat is normally dissipated to the environment by several means. The primary mechanism involves the conduction of thermal energy from the tissues to the circulating blood, where the heat is transported (convected) to the body surface; it is then eliminated by conduction, convection, evaporation, or radiation. Most important is the maintenance of an isothermal body core temperature throughout a range of environmental conditions. However, the heat-transfer processes are largely influenced by external environmental conditions. In warm or hot climates, heat removal from the body may be especially limited and will be further affected by a change in metabolic rate. Remarkably, heat production may be accelerated from rest by a factor of 10 to 15 during extremely heavy work. Therefore, both the external (environmental) and internal (metabolic) heat load affects the body's ability to thermoregulate. When the heat load is heavy, the entire cardiovascular system is taxed and work performance becomes compromised. Wearing the CDE under these circumstances may easily overburden the body's thermoregulatory system and ultimately lead to heat illness or heat stroke unless preventive or mechanical intervention is practiced.

PHYSIOLOGICAL STUDIES OVERVIEW

Wearing individual protective equipment (IPE) such as the chemical defense battle dress overgarment (BDO) can be debilitating from a thermal balance standpoint. Auxiliary personal cooling has been suggested to provide relief or significant attenuation from this heat stress. The armed forces have evaluated various microclimate cooling approaches which might be implemented in the field. The USAF first investigated both in-house and commercial "backpack" (ambulatory) systems. The heat sinks here were either an ice slush or refrigerant. Both approaches were configured in a recirculating closed-loop configuration. In collaboration with the U.S. Army, an open-loop freon-based system was additionally tested. The physiological payoff from these systems was always relatively low; often the estimated "logistical tail" in the field would have been prohibitive. A novel concept of marrying the required rest cycles with personal cooling (intermittent cooling) was later investigated. Both chilled liquid and air intermittent cooling approaches appeared promising in the laboratory. This microclimate cooling concept, later termed Multiman Intermittent Cooling System (MICS), incorporated chilled air in an open-loop configuration. Finally, a simplified, lightweight, ambient air cooling approach was tested for its human efficacy in the environmental chambers. Again, this concept appeared promising as a partial near-term answer to this difficult problem. Finally, a summary of each USAF human physiological study is included in this report.

BACKPACK COOLING STUDIES

Study #1 (Chamber Trials of LSSI Unit)

This study evaluated a commercially produced liquid cooling system suggested for ground crew application which consisted of a liquid cooling vest and cap; it was manufactured by Life Support Systems, Inc. (LSSI). Prefrozen ice cartridges functioned as the heat-sink. In all experiments, the subjects (N=5) wore fatigues, the chemical defense ensemble Mission Oriented Protective Posture (Maximum Level) (MOPP IV configuration) plus a flak jacket. For all liquid cooling trials, the cooling vest and cap was worn next to the skin; the LSSI support system (ice cartridges, power pak, etc.) was donned last. Two chamber environments were employed: 32/21/38°C (warm) or 38/24/44°C (hot) dry bulb temperature (T_{db}), wet bulb temperature (T_{wb}), and black globe temperature (T_{bg}), respectively. The work consisted of treadmill walking for 12 min followed by a 3-min rest period; the sequence was repeated until the termination of the experiment, which was usually because core temp = 39°C. The time-weighted metabolic rates were approximately 400 kcal hr^{-1}. Subjects attempted a maximum trial of 2 hours unless limited by high body core temperature or heart rate ($\geq$ 85% HR max). There were four experimental conditions: (a) warm/control vs. warm/cooling vest and (b) hot/control vs. hot/cooling vest. In all figures, the lines represent the mean values for all subjects exposed to a condition; the line terminates as the first subject is withdrawn. The points indicated by letters represent the final value for each subject and show the interindividual variation in physiologic responses.

The use of the LSSI vest improved tolerance times an average of 36 and 37 minutes for the warm and hot environments, respectively. However, the cooling vest did not eliminate the thermal burden from wearing the CDE. The rate of heat conductance by the vest was quite variable during these experiments (Table 1a). The range was 59 to 160 kcal/hr which represented 15% to 40% of the metabolic heat load.

These data provide only modest support to the concept of liquid cooling as an effective means of removing heat from working ground crew members wearing CDE. The adequacy of the system evaluated for field use will be determined based on operational requirements. Improvements in this or similar systems will be needed to eliminate the thermal burden and to allow prolonged work in the CDE because many logistical support concerns remain.

Table 1a. **Summary of Physiological Responses. Mean (±S.E.).**

Condition	Exposure Time (min)	Rate of Rise in T_{re} (°C/hr)	Metabolic Rate (kcal/hr)	Vest Heat Removal Rate (kcal/hr)	Sweat Loss (%wt/hr)
Warm Control	62 ± 3	1.7 ± .2	409 ± 29	no vest	4.36 ± 1.8
Warm w/Vest	98 ± 26	1.0 ± .4	418 ± 15	100 ± 23	2.76 ± .6
Hot Control	56 ± 10	1.9 ± .1	397 ±15	no vest	4.20 ± .83
Hot w/Vest	93 ± 24	1.0 ± .2	403 ± 7	105 ± 21	3.78 ± .36

The heat removed by the vest somewhat retarded the rate of heat storage. Rectal temperature (T_{re}) rose more slowly during experiments with the vest compared to the control condition (Figure 1a). However, equilibrium core temperature was never achieved; the final T_{re} normally exceeded the goal equilibrium T_{re} of 38.5°C. Heart rate responded similarly; i.e., each exercise period elicited a higher HR than the one before, and each rest period showed less HR recovery than the previous rest period (Figure 1a). Mean weighted skin temperature (mean T_{sk}) was lowered with the vest (Figure 1b). However, the mean T_{sk} was usually substantially higher than Fanger's comfort range for this workload. The cooled T_{sk} was always warmer than the 26°C goal which was established by agreement prior to testing.

In summary, with the use of this commercial cooling system, under "warm" and "hot" conditions, the authors suggest that tolerance time was increased approximately 40 minutes (range = 10 to 54 minutes). However, the thermal burden of wearing the CDE overgarment was not eliminated. Body core temperature (T_{re}) and HR continued to climb during each experiment without indication of thermal equilibrium. The skin temperature under the cooling vest was too warm to inhibit heat storage effectively. Sweat loss remained in excess of 1.5% of body weight per hour.

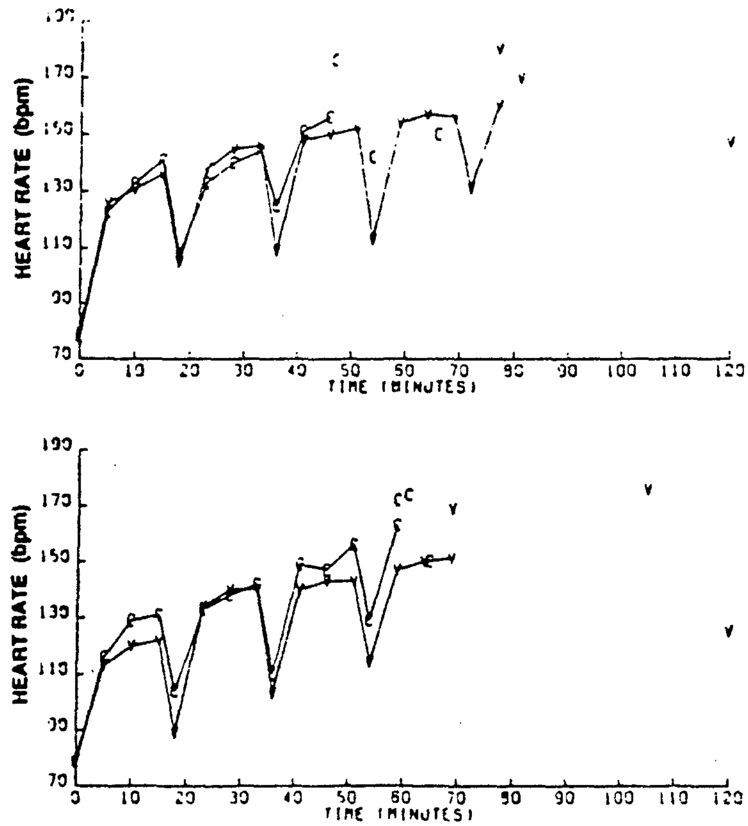


Figure 1a. Means and final HR in hot (top) and warm (bottom) environments. C = Control Tests; V = Cooling Vest Tests.

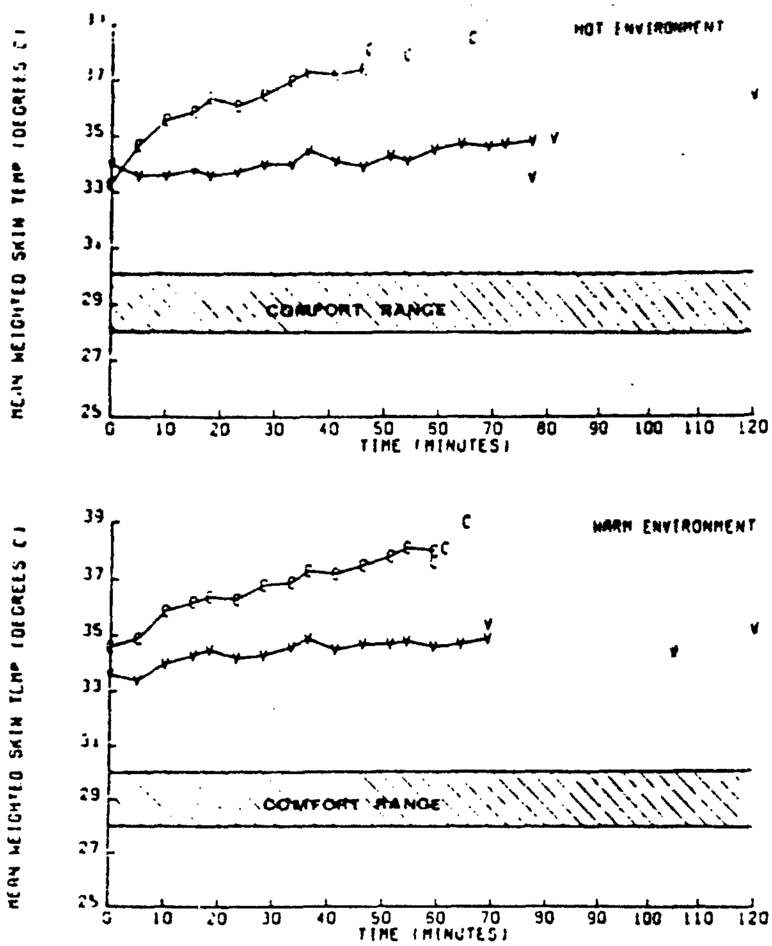


Figure 1b. Means and final mean skin temperatures.
C = Control Tests; V = Cooling Vest Test.

Study #2 (ILC and LSSI Chamber Trial Comparisons)

In these experiments, two commercially available backpack (i.e., body-mounted) liquid-cooling systems (LCS) were tested on both a completely wet (maximal sweating) copper manikin and with human subjects (N=9) wearing the CDE (MOPP IV). The tested systems are manufactured by ILC Dover (ILC) and Life Support Systems Incorporated (LSSI). Both systems, using ice as the heat sink, cool the torso by establishing a thermal gradient between the body surface and cool liquid circulating in the garment. The LSSI system also incorporated a liquid-cooled cap. The manikin was dressed in a cooling garment and the complete CDE and placed in a standing position in a large temperature- and humidity-controlled chamber; conditions were (T_{db}/T_{wb}): (a) hot (45/31°C) or (b) warm (32/22°C). The heat loss from the copper manikin was determined by measuring the power (Watts) required to maintain a constant manikin surface temperature. In this study, electricity was supplied to the torso to maintain an average temperature of 35°C; the head section was also heated to 35°C in tests on the LSSI system, since it included a cooling cap as well. The "cooling period" started at time zero when the ice packs were inserted into the heat exchanger and the pump motor was switched on.

The heat exchange provided by both the ILC and LSSI systems is plotted against time in Figure 2a. Heat loss from the manikin's surface was essentially the same at wet-bulb globe temperature (WBGT) indexes of 24.7 and 35.9°C, indicating that the heat sinks were well insulated from the outside environment. The cooling supplied by the ILC and LSSI units over the initial 2h averaged 74 W and 75 W in the 24.7°C WBGT environment, and 66 W and 68 W respectively in the 35.9°C WBGT environment. Not surprisingly, cooling provided by both systems diminished over time. Cooling has been shown to increase with agitation of the ice cartridge (Figure 2b). Thus, the amount of heat transfer measured on the passive copper manikin would be less than that measured on a human subject in motion.

Human subjects walked on a treadmill at 3.3 mph, 5% grade. Environmental conditions ($T_{db}/T_{wb}/T_{bg}$) were: hot = 45/31/50°C and warm = 32/22/37°C, respectively. The exercise consisted of alternating work (10 min) and rest (3 min) cycles with an estimated metabolic cost of 390-427 kcal hr^{-1} (time weighted). This regimen continued for 165 min, or until one or more of the following termination criteria was reached: (a) HR exceeded 180 bpm, (b) T_{re} exceeded 39.0°C, or (c) the subject was unable to continue. The rectal temperature, heart rate, and mean skin temperature responses (hot conditions) are displayed in Figures 2c, d, and e, respectively.

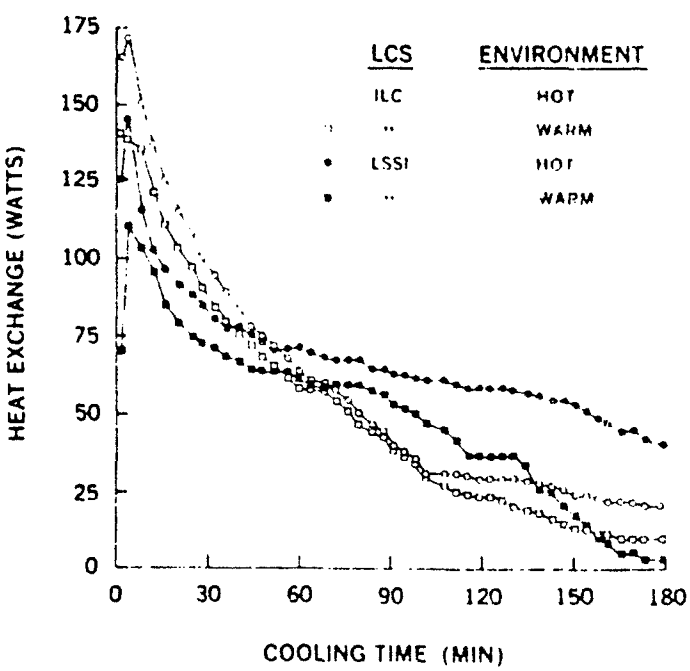


Figure 2a. Heat exchange provided by the ILC and LSSI liquid cooling systems on a wetted manikin.

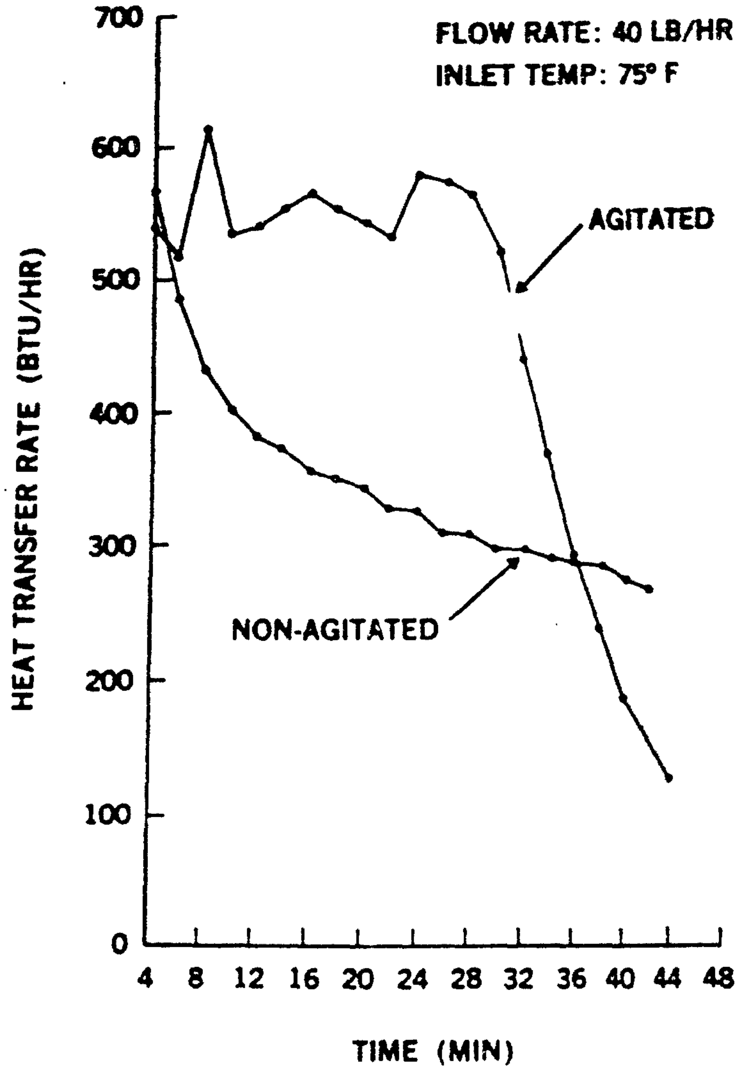


Figure 2b. Effects of physical agitation of ice cartridge (LSSI) on heat transfer.

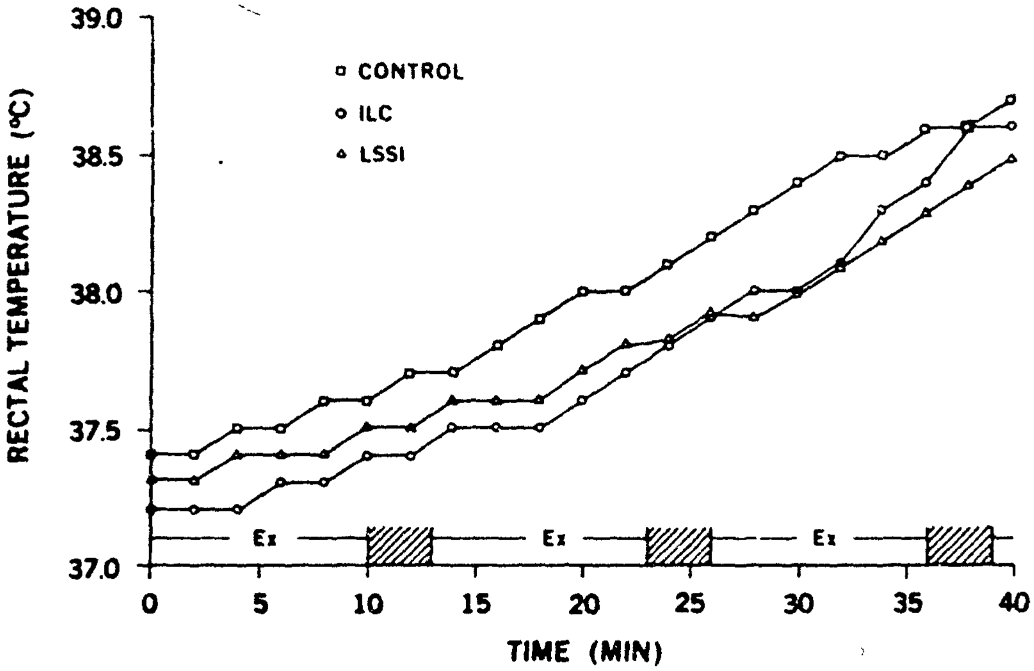


Figure 2c. Rectal temperature response under three experimental conditions in a hot environment.

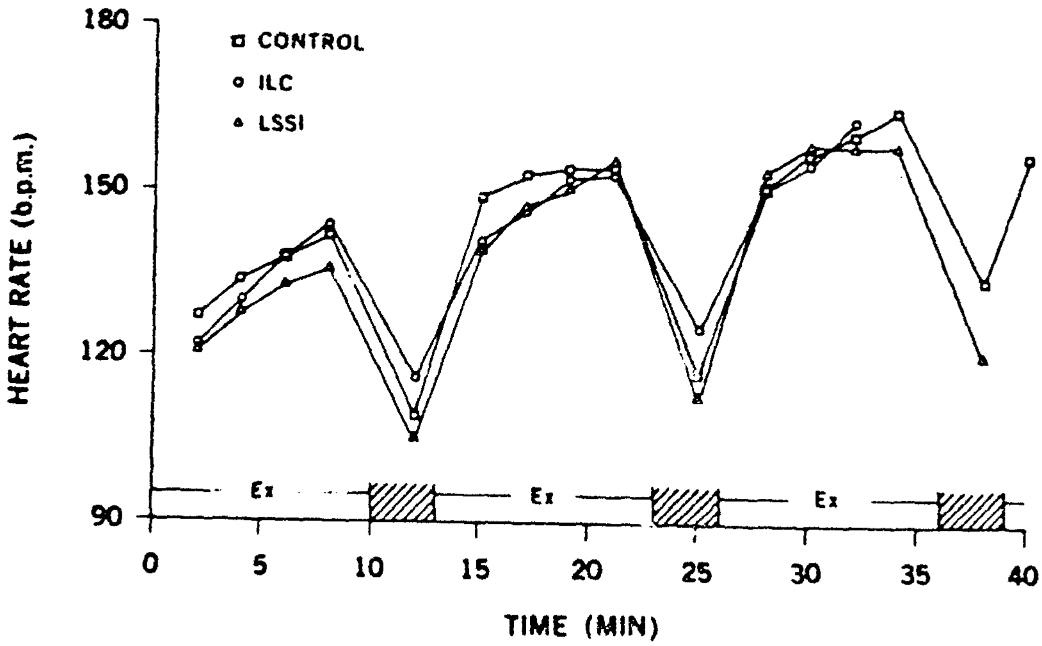
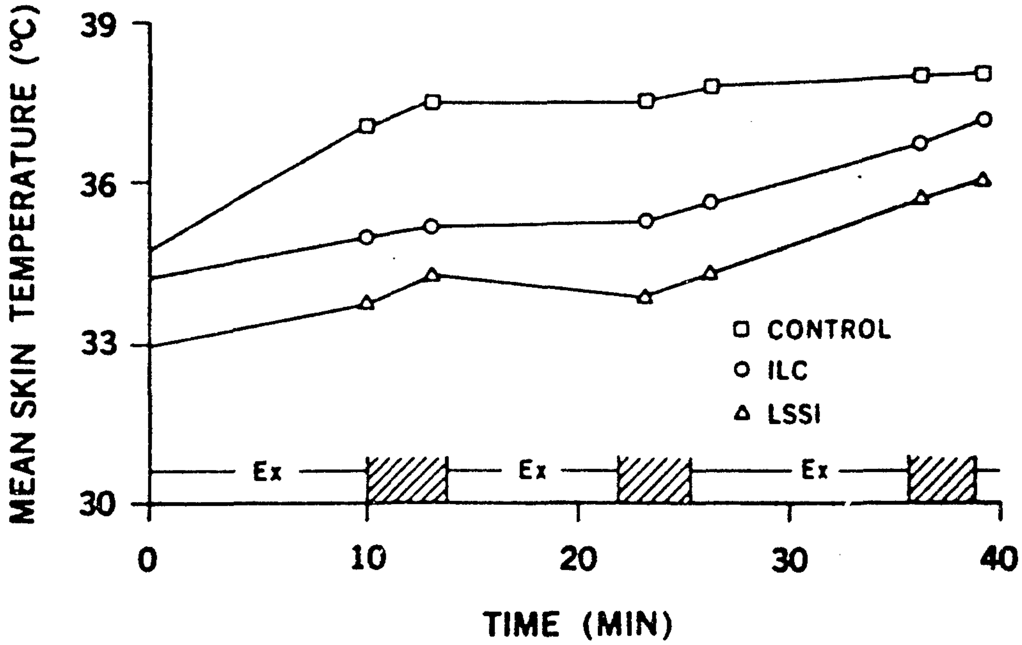


Figure 2d. Heart rate response under three experimental conditions in a hot environment.



2e. Mean skin temperature response under three experimental conditions in a hot environment.

Hot Conditions (WBGT = 35.9°C)

After the beginning of treadmill work, T_{re} rose at a rate of 2.4°C hr^{-1}, and this rise was not influenced by either cocling system: at 39 min of exposure T_{re} ~ 38.5°C for all trials (Figure 2c). During the first three exercise bouts the mean HR rose by roughly 50 bpm (Fig. 2d). There were no differences in mean HR at the start of the experiment (124 bpm) or at the end of the third exercise bout (170 bpm). Sweat production and evaporation values are given in Table 2a. No differences among conditions were observed in sweat rates or evaporation. Figure 2d gives the data for T_{sk} under each of the experimental conditions. Both cooling systems decreased T_{sk} during the initial 30 min of exposure, but at 39 min these differences were insignificant. The cooling systems caused no change in the exposure time at which tolerance limits were reached. Therefore, neither of these personal cooling systems provided a significant thermal advantage over control under these conditions.

Table 2a. Sweat and Evaporative Weight Loss. Mean (±S.E.).

Condition	Total Weight Loss (% Body Wt hr^{-1})	Evaporative Weight Loss (% Total)	Sweat Rate (kg hr^{-1})
Hot Control	2.48 ± 0.53	34.5 ± 11.4	1.877 ± 0.368
ILC	1.81 ± 0.28	18.8 ± 4.9	1.425 ± 0.183
LSSI	1.89 ± 0.38	18.1 ± 4.7	1.509 ± 0.253
Warm Control	1.87 ± 0.24	19.9 ± 6.0	1.353 ± 0.262
ILC	0.78 ± 0.48	65.0 ± 25.0	0.559 ± 0.346
LSSI	1.05 ± 0.07	41.9 ± 2.2	0.742 ± 0.061

Warm Conditions (WBGT = 24.7°C)

There was some difficulty in comparing the two cooling systems because the ice had completely melted in both chillers by 75 min. The ILC system could not be recharged because, to do so, the overjacket and fatigue shirt had to be removed. Therefore, the ILC trial was ended after 75 min; however, the LSSI was easily recharged and the exposure time was extended to 165 min.

Mean T_{re} values are given in Figure 2f. Rectal temperature rose at a rate of 1.7°C/h without an LCS and reached a mean value of 38.8°C in 52 min. Both of the cooling systems significantly reduced the rate at which T_{re} increased: the ILC by 35% (1.1°C/h) and the LSSI by 47% (0.9°C/h). There were no significant differences between the ILC and LSSI units during the first hour of the experiment. Equilibrium levels of T_{re} ranged between 38.2°C and 38.4°C during the final 1.5 h of exposure with the LSSI unit. The mean heart rate (118 bpm) at the beginning of the experiment did not differ between experimental groups (Fig. 2g). Without auxiliary cooling, all of the subjects were removed at a mean exposure time of 52 min, primarily because HR exceeded 180 bpm. By the end of the fourth exercise period, the mean HR was 164 bpm without cooling and 150 bpm with either LCS. During the final 1.5 h of exposure with the LSSI system, the mean HR was 146-160, with full recovery to pre-exposure rates during many of the 3-min rest periods. Mean skin temperatures are shown in Figure 2h. The mean sweat rate was reduced to 41% and 55% of the control value (1.353 kg/h) by the ILC and LSSI cooling systems, respectively (Table 2a).

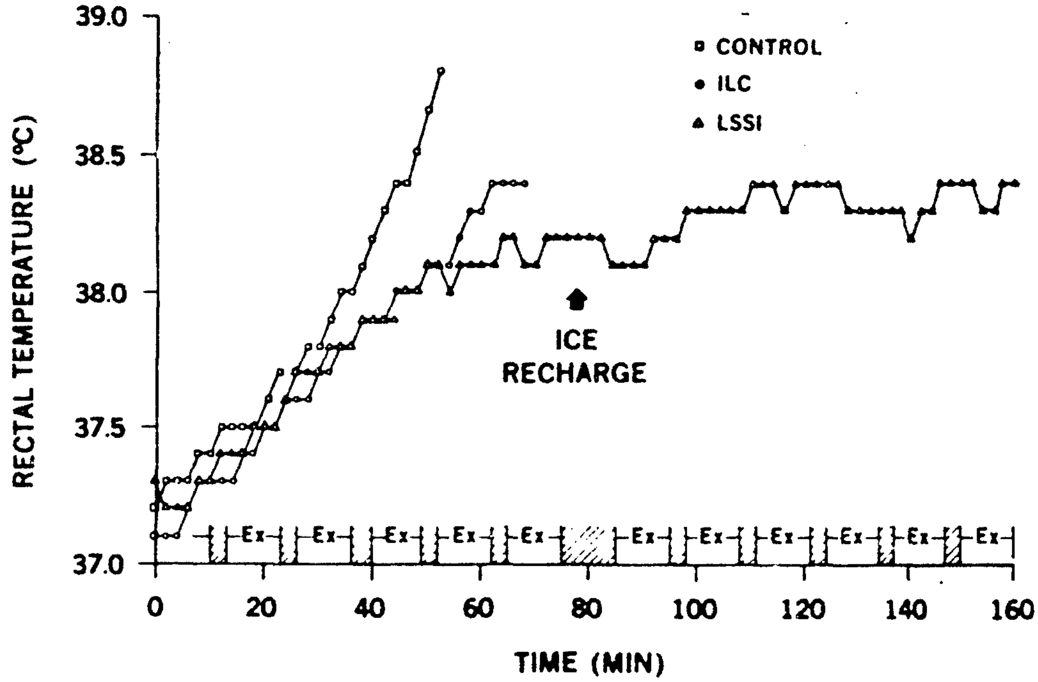


Figure 2f. Rectal temperature response under three experimental conditions in a warm environment.

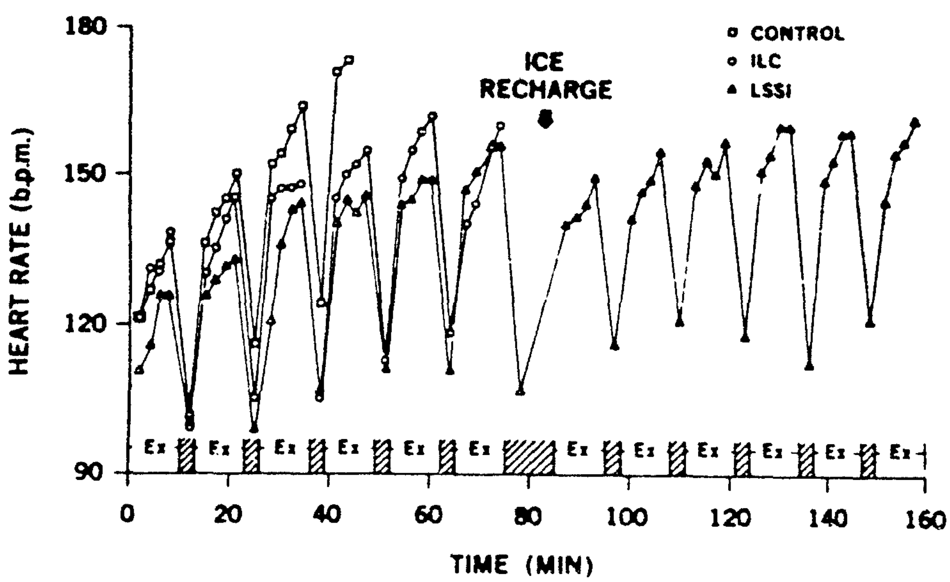


Figure 2g. Heart rate response under three experimental conditions in a warm environment.

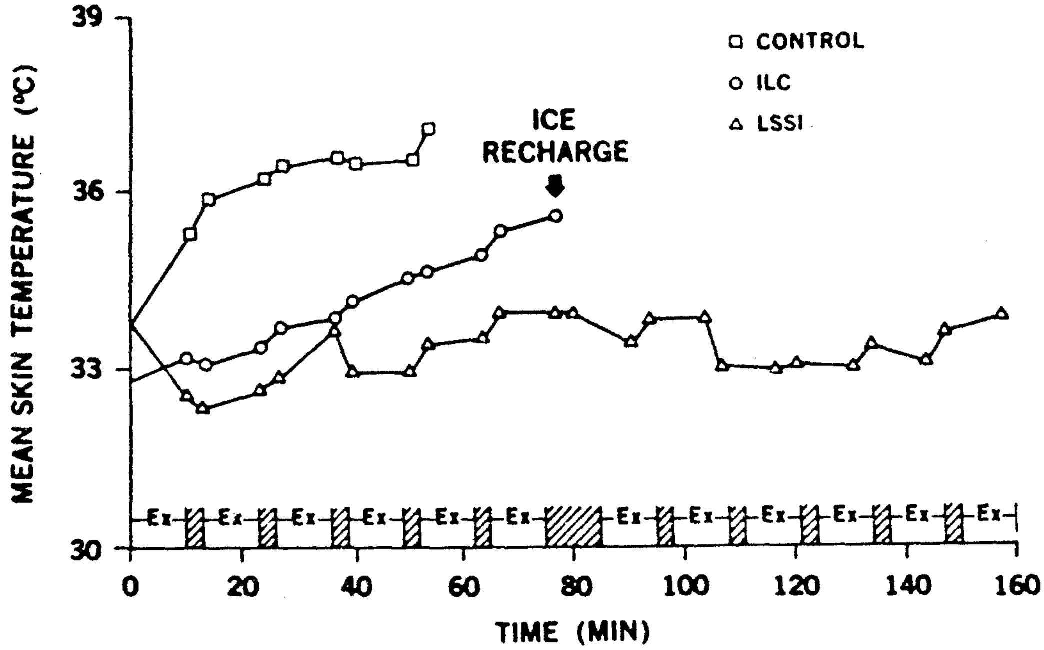


Figure 2h. Mean skin temperature response under three experimental conditions in a warm environment.

The mean tolerance time for the LSSI condition was 155 min. All of the subjects tested with the ILC chillers were removed after the sixth work bout, without reaching an experimental end point.

When the environmental heat load was less severe (24.7°C WBGT), both systems significantly reduced physiological strain. The LSSI system was more effective in this respect; both T_{re} and HR reached reasonable plateau values, which for T_{re}, T_{sk}, and HR were 38.3°C, 33.0°C, and 146-160 bpm, respectively. Sweat rates were also significantly reduced.

These researchers noted two important points: (a) that available portable liquid cooling systems can greatly enhance the ability of subjects to tolerate working in moderate heat while wearing a highly insulative overgarment, and (b) that a severe environmental heat load (WBGT > 35°C) negates the thermal advantage from these particular systems. However, neither of the systems as tested was found suitable for USAF field operating conditions.

Study #3 (USAF Prototype Liquid Cooling System)

In Study #3, the physiological response to the use of a developmental liquid cooling system was evaluated. Again, the goal was to alleviate heat stress in personnel wearing the standard chemical defense ensemble (MOPP IV) configuration.

The prototype human-mounted portion of the system consists of a liquid-cooled garment (LCG) and a backpack. The backpack, which supports the heat sink, pump, and battery, was worn on the back with the weight evenly distributed between the shoulders and hips. The LCG is constructed of Tygon tubing interwoven into an elasticized net jacket. The total tubing length is 96 meters, and the effective cooling surface in contact with the skin is 0.52 square meters. The LCG extended from the hips across the shoulders and above the elbows so that the full torso, the shoulders, and the upper arms received active cooling. In each experiment, the subjects followed a work/rest cycle of 15 minutes exercise followed by 3 minutes of rest until the experiment terminated. Each experiment continued until one of four termination criteria was reached: T_{re} reached 39°C; HR reached 85% of age-predicted maximal; the subject reported intolerable fatigue; or 3 hours had elapsed.

This developmental backpack cooling system was tested in environmental conditions of $T_{db}/T_{wb}/T_{bg}$ = 38/24/44°C. Most of the data presented in this report was confined to workloads of 415 kcal/hr (time-weighted average). A few trials were evidently conducted at other temperatures and work rates, but were not fully reported. The subjects exercised at a time-weighted metabolic rate of 415 kcal/hr in the 38/24/44°C environment.

Figures 3a and 3b present the responses of rectal temperature (T_{re}) and mean skin temperature (T_{sk}) in 5 subjects. A visual comparison with a commercial cooling system developed by Life Support Systems, Inc. (LSSI) is provided. These subjects had a mean tolerance time of 56 ± 10 minutes without cooling. During control experiments both T_{re} and T_{sk} rose continuously until the tolerance limit was reached and the subjects were removed from the thermal chamber. When subjects wore the LCG, all experiments continued for the full 3-hour time limit. Subjects reached an equilibrium T_{re} of 38 ± 0.1°C which was sustained throughout the experiment. The effect of liquid cooling on sweating response is presented in Figure 3c. When subjects wore the system, but without auxiliary cooling, total sweat production was 1.37 ± .41 L/hr. The fractional portion of this sweat production which was evaporated was 0.33, representing an efficiency of sweat output of 33%. Personal cooling reduced total sweat production to 0.69 ± 0.19 L/hr, while the efficiency of sweating was 55%. The total heat dissipation measured during these experiments is presented in Figure 3d. During control experiments, the only source of heat dissipation was evaporation of sweat. Sweat evaporation afforded 273 ± 40 kcal/hr of heat removal. The cooling vest and backpack restricted evaporation somewhat more than the CDE alone, resulting in heat removal by evaporation of 219 ± 30 kcal/hr. The auxiliary heat removal via personal cooling was 240 ± 47 kcal/hr resulting in a total heat removal rate of 459 ± 36 kcal/hr.

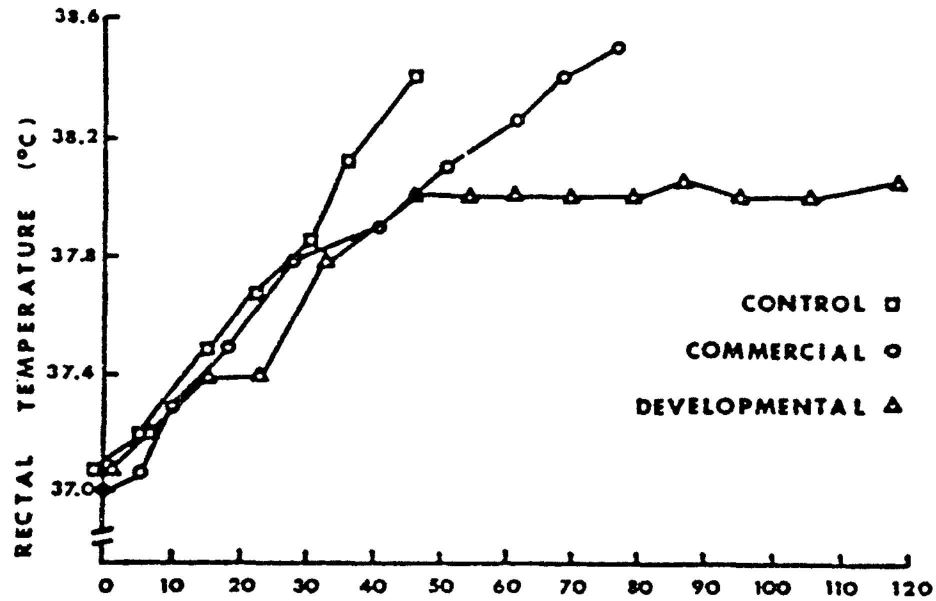


Figure 3a. Rectal temperature response under three experimental conditions in a warm environment.

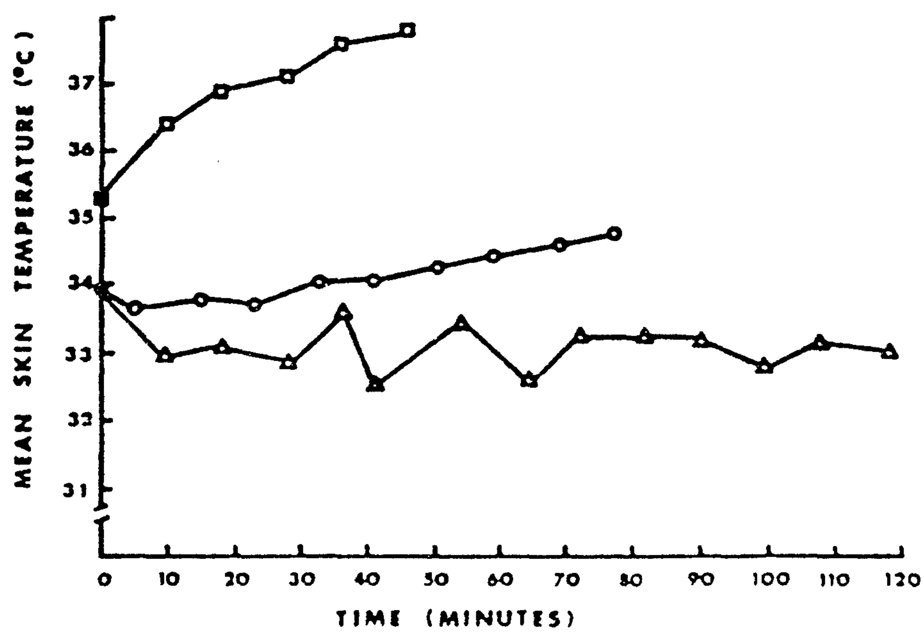


Figure 3b. Mean skin temperature response under three experimental conditions in a hot environment.

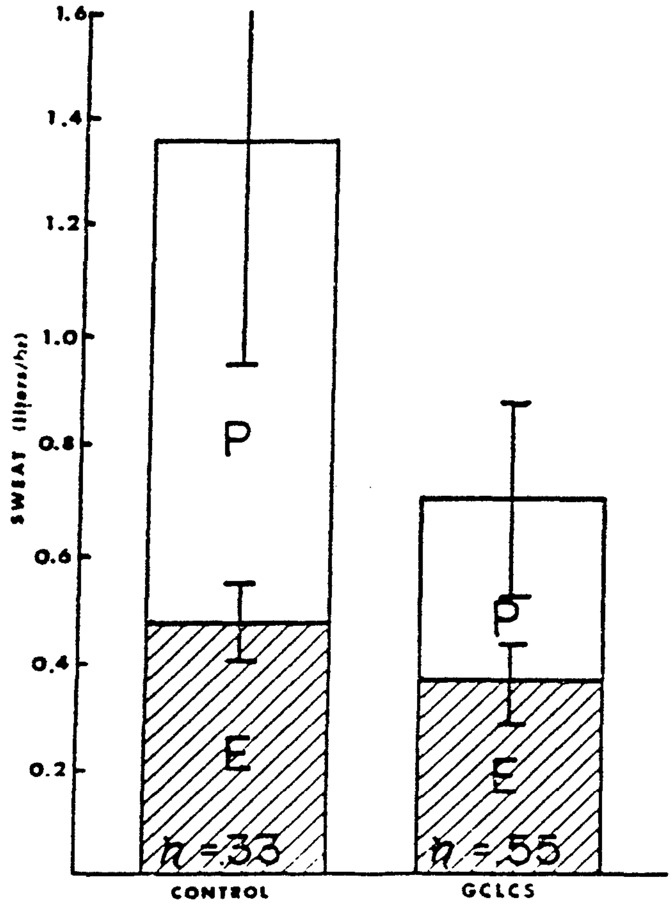


Figure 3c. Sweat production without (control*) and with (GCLCS) liquid cooling. * cooling system still donned.

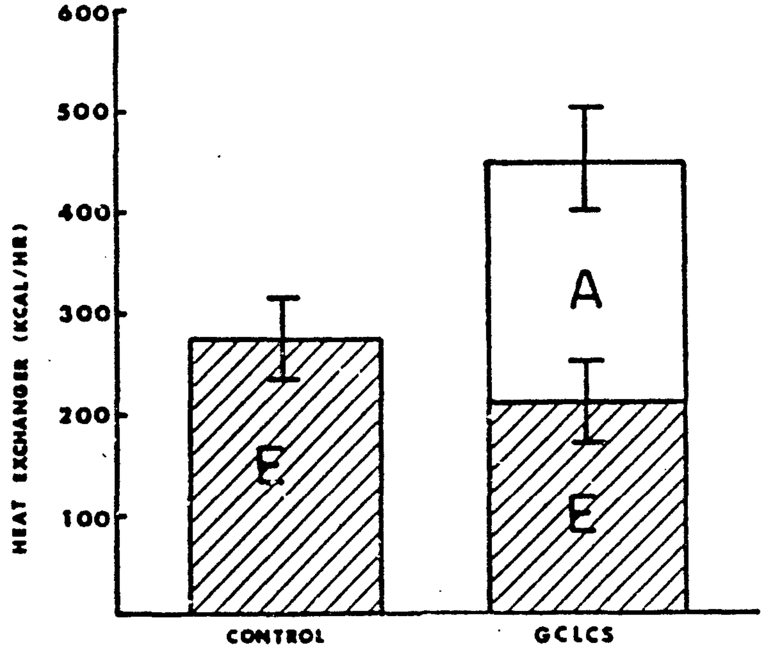


Figure 3d. Total heat loss without (control*) and with (GCLCS) liquid cooling. * cooling system not donned.

Figure 3e presents a continuum of heat tolerance envelopes; it summarizes the envelopes of environments and workloads which can be tolerated by ground crew working in the near-term CDE. The clear area represents the tolerance envelope for the CDE with no auxiliary cooling. When environmental conditions are such that heat is neither gained nor lost via radiation and convection (see point a), approximately 219 kcal/hr of metabolic heat can be dissipated to the environment. As heat gain from the environment increases, the metabolic heat which can be tolerated decreases as is indicated by the downward trend of the tolerance envelope. The uppermost hatched area defines the tolerance envelope for the Ground Crew Liquid Cooling System (GCLCS) described herein. The metabolic heat production which can be tolerated is increased by the 240 kcal/hr which can be expected to be absorbed by the LCG. When heat is neither gained nor lost via radiation or convection, the total tolerable metabolic heat load is approximately 459 kcal/hr (see point b). For comparison, the tolerance envelope measured for the LSSI system is presented as well.

The investigators concluded that the prototype personal cooling system did not dissipate enough heat to fully eliminate the thermal burden of wearing the CDE in all environmental extremes and under all workloads. However, many USAF ground crew tasks can be accomplished with the heat removal afforded by this system. Jobs with very high workloads, such as rapid runway repair, could be continued in hot weather for only limited time periods (approximately 2.5 to 3 hours).

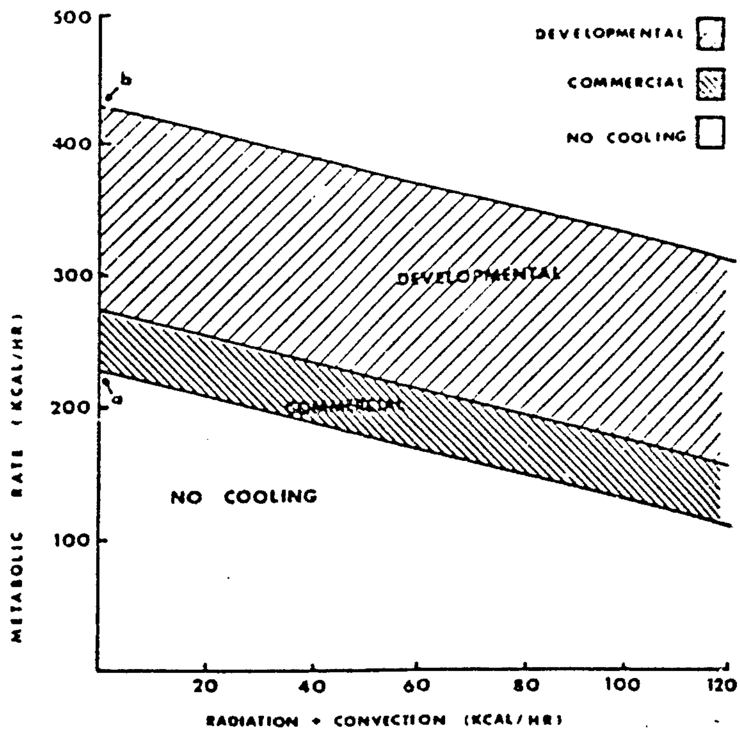


Figure 3e. Heat tolerance envelopes in subjects wearing the CDE (MOPP IV) performing work. The addition of a commercial and development cooling system is compared (see text).

Study #4 (Field Evaluation: Liquid Cooling and Training)

Study #4 evaluated the effects of proper training, careful pacing, and adequate personal cooling on task performance. Thirteen male volunteer subjects performed rapid runway repair (RRR) exercises in a total of five experiments over as many days. These volunteers from an active duty squadron were mostly young enlisted members with an estimated aerobic capacity of 35.2 ml/min/kg. Each subject was tested while wearing: (a) the full USAF ground crew CDE with all apertures closed (Closed), (b) a portable water-cooling system under the closed ensemble (Closed w/Cooling), and (c) standard fatigues with a protective hood and mask (Open). The ranking RRR team member was assigned the additional task of setting the work pace at as high a level as deemed possible under the prevailing circumstances and without incurring unnecessary "casualties." Training effects were assessed by testing all subjects in the

Closed condition on experimental days 1 and 5. On the intervening days, each subject was tested in the Open and Closed w/Cooling conditions in a random order. Comparisons were made of physiological responses (rectal temperature - T_{re}; heart rate - HR; sweat rate - SR) under the three experimental conditions to quantitatively assess the thermal strain contributed by the CD overgarments (Open vs. Closed), and the extent to which auxiliary cooling alleviated this thermal burden under field conditions (Open vs. Closed w/Cooling). The liquid cooling system employed here was not further characterized. Performance was assessed by documenting the rate of task completion and total amount of work performed, but was not reported. The mean environmental temperatures over the five exposure periods were as follows: 29.6_{db}, 24.8_{wb}, and 38.3_{bg}°C.

Figures 4a and 4b graphically summarize the key physiological data. Figure 4a.a. shows that body heat storage (T_{re}) continued to rise at roughly 0.6°C/hr, and that five days of training significantly reduced the cardiovascular strain associated with performing RRR in a CD posture ($p < .001$), (Fig. 4a.b.). The observed reduction in HR cannot be attributed to a difference in the environmental heat load on days 1 and 5. Personal observations of and interviews with the subjects suggested that mask intolerance, rather than physiological endurance, was the primary factor in limiting military effectiveness in the initial exposure (day 1). The conclusion reached by these investigators was that none of the casualties incurred on day 1 was due to excessive heat storage. The result of an improvement in performance was attributed to the training. Auxiliary cooling was suggested to further enhance performance by virtue of its ability to eliminate the thermal burden imposed by the CD overgarments. Over the initial 75 min of exposure, T_{re} climbed to a mean value of 38°C, regardless of the experimental condition. Once the mean value for T_{re} reached 38°C in both the Closed w/Cooling and Open conditions, no further body heat storage occurred for more than 2 additional hours (Fig. 4b). It was concluded: (1) that the auxiliary cooling provided by the water-cooling system used in this study had eliminated the thermal burden imposed by the CD overgarments, and (2) that the data (not reported) for HR and SR tended to support this conclusion. However, no comparisons were made with a true control, i.e., no CDE. These investigators concluded that the military effectiveness of a well-trained unit, which must perform strenuous work (RRR exercise) in a full CD posture, can be greatly enhanced by the provision of commercially available portable cooling systems. Unfortunately, the direct effect of "self pacing" on metabolic rate was not quantified here. This omission seriously clouds some of the investigators' conclusions.

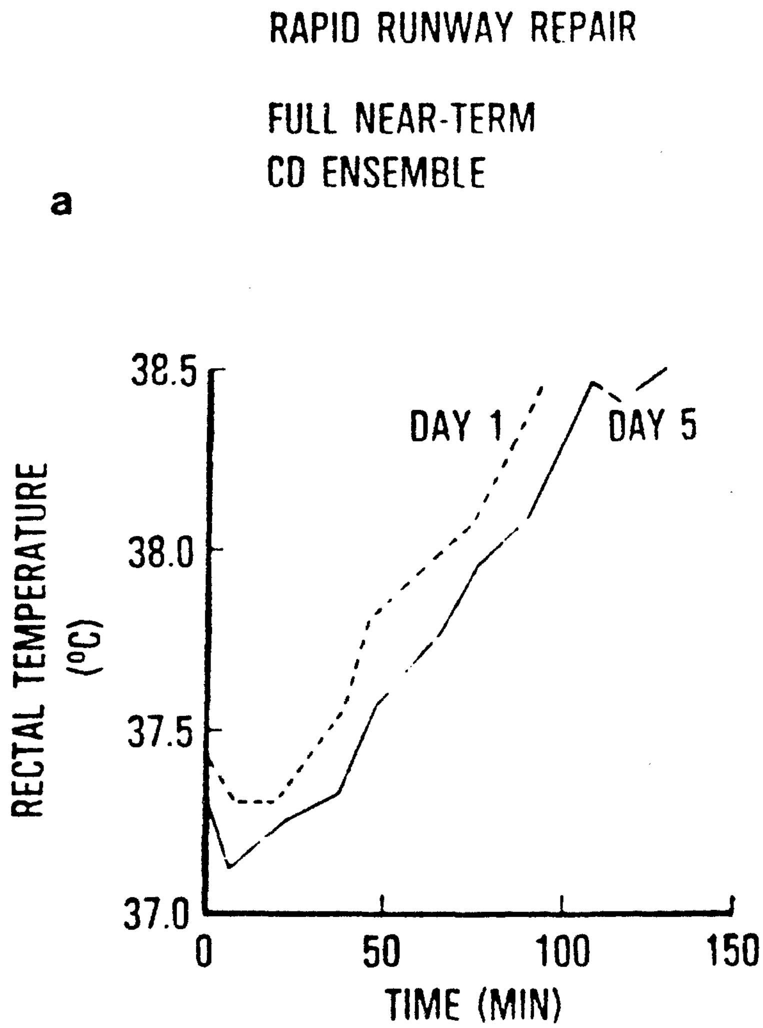


Figure 4aa. Effect of training on rectal temperature response during heavy work in the CDE.

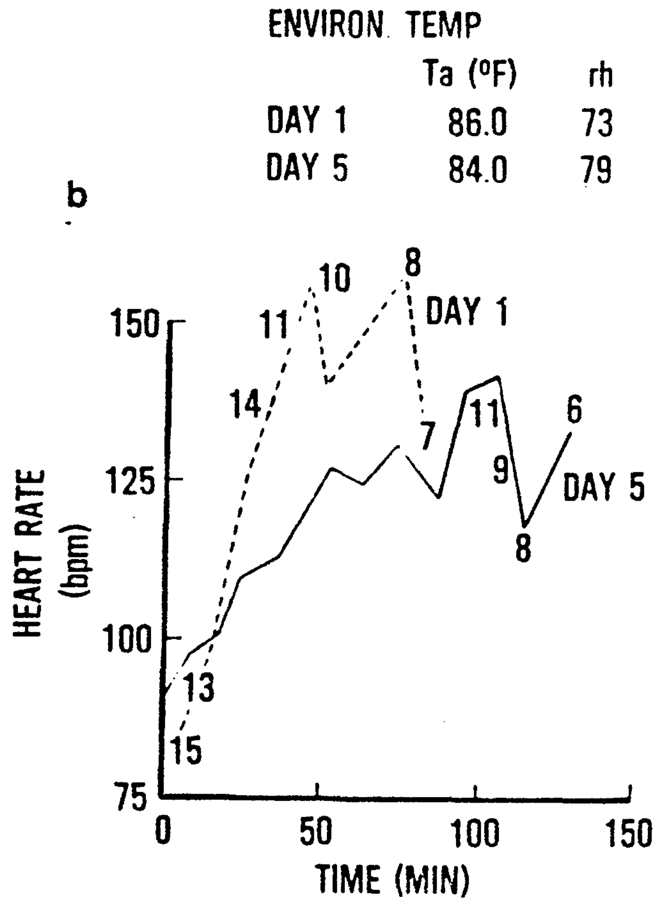


Figure 4ab. Effect of training on heart rate response during heavy work in the CDE.

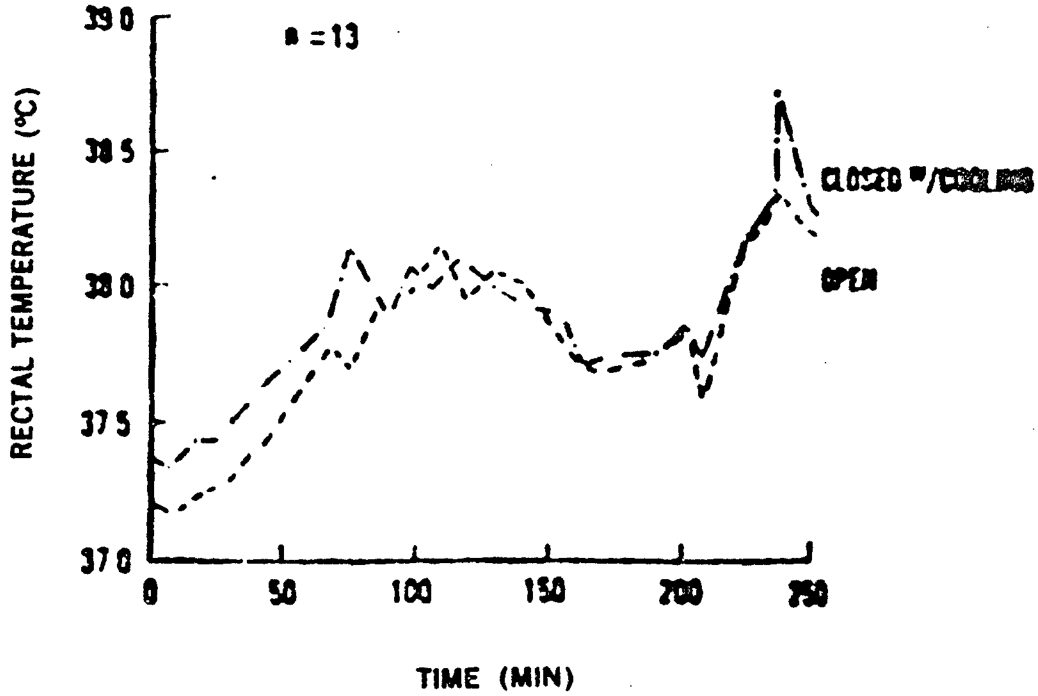


Figure 4b. Rectal temperature response to heavy work while wearing the CDE open and the CDE closed with personal cooling.

Study #5 (Open-Loop Freon Cooling Chamber Trials)

Study #5 which was carried out with the collaboration of the U.S. Army (Natick Research Development and Engineering Center (NRDEC, USARIEM, performing labs), evaluated three commercially available, portable microclimate cooling systems. The three selected were: the Model 19 Cool Vest manufactured by ILC Dover, the Cool Head manufactured by Life Support Systems, Inc. (LSSI), and the Thermacor Vest manufactured by Thermacor Technology, Inc. The ILC system was a new configuration; the Thermacor vest represented a new technology. The first two systems relied on melting ice as the sink to remove metabolic heat. The Thermacor system provided cooling by extracting heat from the wearer's body; this heat energy changed the refrigerant (a chlorinated fluorocarbon) from a liquid to a gas.

Five male volunteer soldiers served as test subjects. The environment for each session was maintained at 38°C (100°F) dry bulb temperature and 11.7°C (53°F) dew point (21% relative humidity). The wind speed was 1.13 m s^{-1} (2.5 mi hr^{-1}). The test consisted of three 60-minute cycles (50 minutes/10 minutes rest exercise). The subjects walked on a treadmill at 3.0 mi hr^{-1}, 0% grade during their 50-minute work periods. Average measured metabolic rate during the work periods was 440 W. The overall average, including rest, was 384 W. The test subjects wore (in order from the skin outward) a T-shirt, cooling vest, combat vehicle crewman (CVC) fragmentation protective vest, CVC Nomex coveralls, chemical/biological (CB) overgarment (pants and jacket), M-17 gas mask, butyl rubber hood, CB butyl rubber gloves with cotton liners, and CB butyl rubber overboots. The heat absorbed by the Thermacor vest was calculated by weighing the canisters after the test to determine the mass expended. The test was terminated after 180 minutes, when a subject's core temperature reached 39.5°C (103.1°F), or when the heart rate exceeded 180 beats per minute for more than 5 minutes during or immediately following exercise.

The average heat removal rate for each system is shown in Figure 5a. Performance of the ILC and LSSI systems was statistically equivalent (244 ± 68 W and 222 ± 29 W, respectively). However, the Thermacor system provided cooling at a significantly lower level ($p < 0.05$) 108 ± 17 W. The average exposure times for each system are shown in Fig. 5b. All values are statistically different from one another ($p < 0.05$). The ILC system allowed for the longest work times. The exposure times differ because some subjects had to be removed from the chambers due to nausea, dizziness, and headaches. The rate at which T_{re} changed differed significantly between the systems; the Thermacor garment exhibited the most rapid increase in temperature and the ILC system, the slowest (Fig. 5c).

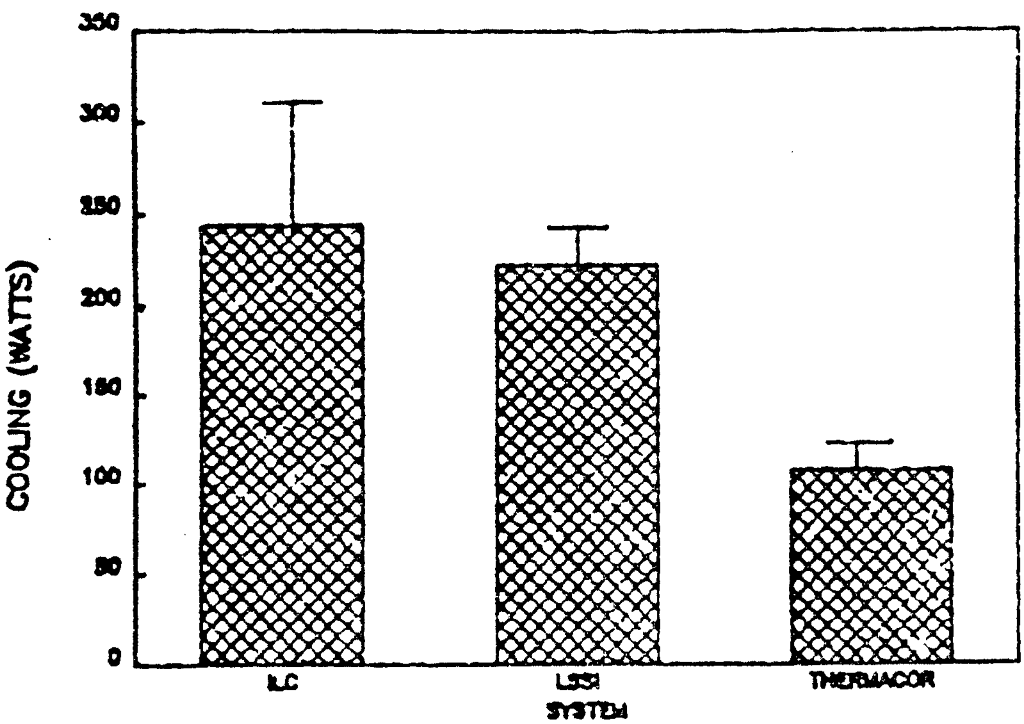


Figure 5a. The calculated cooling values for each system (± S.D.).

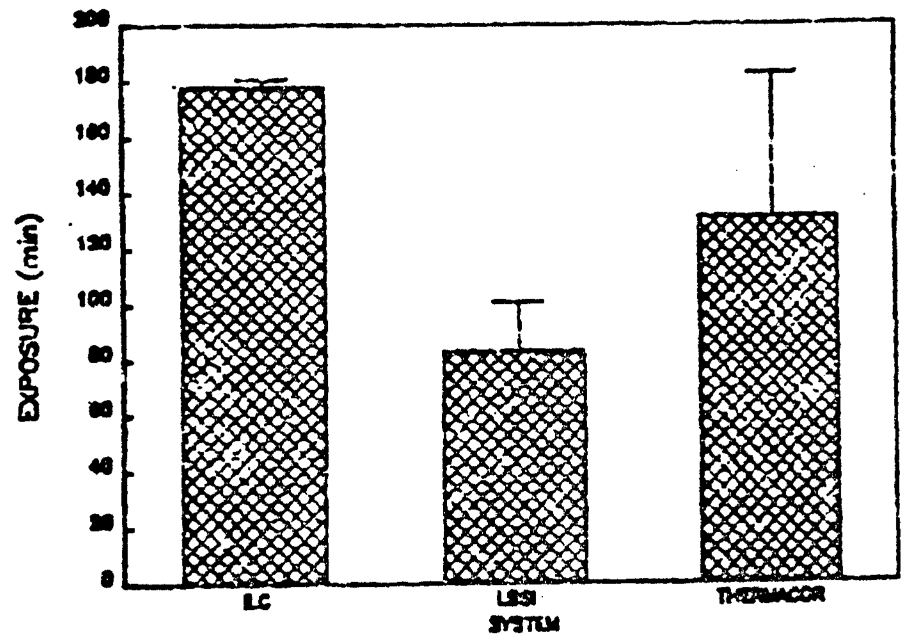


Figure 5b. The observed exposure time in the chamber (± S.D.).

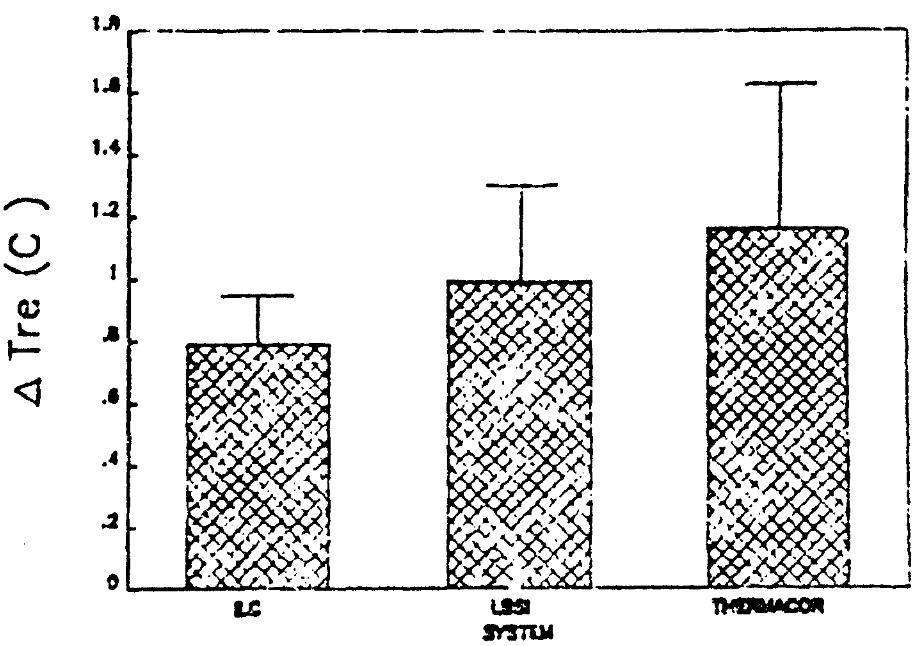


Figure 5c. The observed increase in rectal temperature after 60 min of exposure (± S.D.).

In conclusion, the investigators suggested that all the portable microclimate cooling systems evaluated in this study exhibited features that would make them unsatisfactory for extended field use by the armed forces because of practical and logistical concerns. The LSSI Cool Head allowed for an average exposure time of only 83 minutes despite providing a high rate of cooling. It was suggested that this short cooling period may have been due to the (inefficient) head cooling provided by the system. The Thermacor vest, although providing a greater average stay time for the subjects than the LSSI system, allowed only two of the subjects to continue beyond 2 hours. The Thermacor system also presented a logistical burden; it is necessary either to purchase, store, and issue canisters of R114 or to develop a closed-loop regeneration system. The Model 19 Cool Vest by ILC permitted the highest stay times in the high temperature environment, but it is actually limited to about 2 hours because of the need to leave the contaminated environment and enter a clean environment where the wearer must remove clothing to service the cool vest. Based on the study results, for sorties of short duration (less than 2 hours), only the ILC system combines an adequate cooling rate with minimal logistical burden. It must be kept in mind, however, that the ILC must be worn inside of the protective garment which make it impractical for widespread field use.

INTERMITTENT COOLING STUDIES

Study #6 (Intermittent Liquid Cooling Chamber Trials)

One approach to enhancing total work capacity is to incorporate carefully scheduled rest cycles into the work task. Realizing the limitations of technology currently available, Study #6 researched the efficacy of employing personal microclimate cooling during the obligatory rest periods via a stationary tether. This approach was expected to greatly accelerate heat removal, while avoiding many of the logistical and ergonomic problems associated with ambulatory, backpack systems.

The eight subjects (five men, three women) who participated in these tests, with the exception of a higher aerobic fitness level, were broadly representative of the United States' general labor population. All observations were performed in an environmental chamber at 38°C T_{db}, 26°C T_{wb}, and 43°C T_{bg} (WBGT = 31°C). The following three clothing conditions were studied in a repeated measures design: (1) control, T-shirt and trousers only (C); (2) chemical protective ensemble (CDE, MOPP IV configuration) without auxiliary cooling (CPE); and (3) CPE plus intermittent liquid cooling (COOL). The work consisted of inclined treadmill walking with 30 min walking alternated with 30 min of seated rest. The metabolic rate was set at about 40% of VO_{2max} which resulted in a mean work rate of about 475 W gross (400 W C trial). The "rest" conditions were the same as those for work except no direct source of radiant heat was used to simulate a shaded environment. Walking was stopped if body core temperature reached 39°C or total elapsed time exceeded 240 min. The liquid cooled garment was a snug-fitting, upper torso vest covering approximately 0.5 m^2 of body surface. Chilled liquid was circulated through small-bore Tygon tubing at a rate of approximately 1 Liter/min^{-1}, with a fluid inlet temperature of approximately 13°C.

The rectal temperatures at the end of each work and rest cycle across time for each condition are displayed in Figure 6a. Cumulative heat storage was minimized after the first work/rest cycle in the C trial, and after the second work/rest cycle for the COOL trial. For both end work and rest cycles, independently, the responses of core temperature (T_{re}) over time were significantly different ($p < 0.05$) among the three experimental paradigms. Working heart rates were always lower ($p < 0.05$) in the C condition while no significant differences were noted between CPE and COOL conditions (Figure 6b). Table 6a shows selected physiological responses after the final work period for each condition. Even more marked differences in body temperature between the COOL and CPE trials can be seen after the final rest period (see Table 6b). In general, a review of Table 6b suggests that, when the COOL trial is compared with the CPE trial, the addition of intermittent cooling considerably lowered T_{re} and T_{sk} temperatures relative to the CPE trial.

Table 6a. Physiological Observations at the End of the Final Work Cycle for Each Experimental Condition. Mean (± S.E.).

	Condition		
Variable	C	COOL	CPE
T_{re} °C	37.7 (0.1)	38.2 (0.1)*+	39.0 (0.1)*
T_{sk} °C (chest)	35.6 (0.1)	37.4 (0.2)*+	38.3 (0.2)*
T_{sk} °C (thigh)	35.5 (0.2)	37.2 (0.3)*+	37.7 (0.2)*
Heart rate (bpm)	111 (2.9)	164 (5.8)*	160 (4.2)*

* $p < 0.05$ vs. C
+ $p < 0.05$ vs. CPE

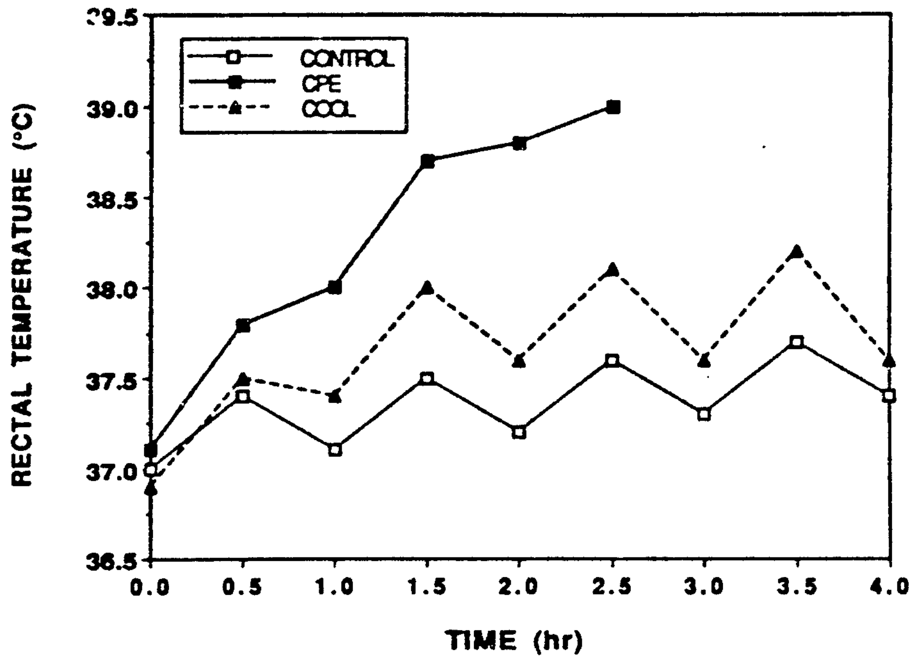


Figure 6a. Mean rectal temperature at the end of each work and rest cycle for three experimental conditions.

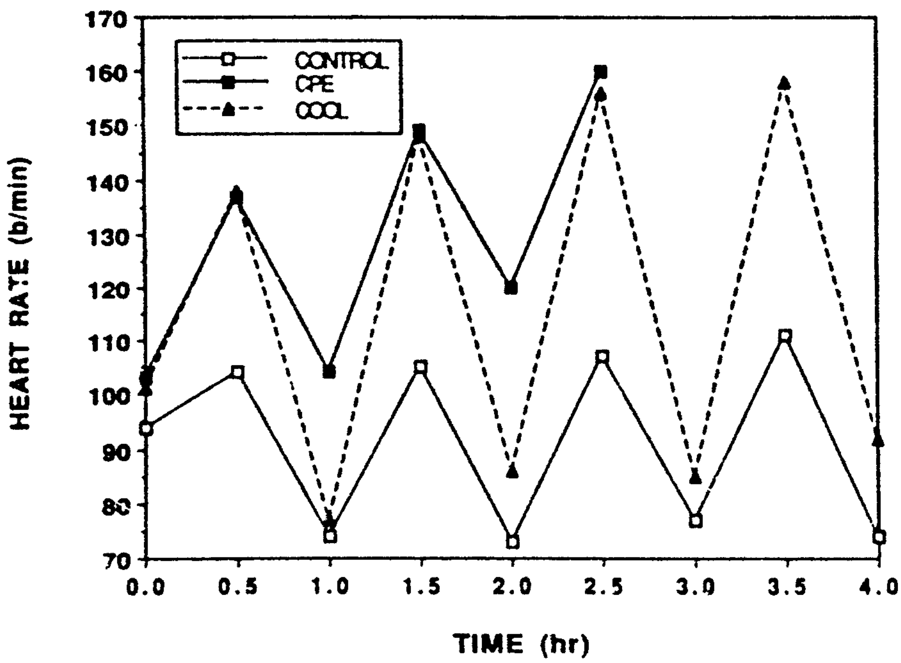


Figure 6b. Mean heart rates at the end of each work and rest cycle for three experimental conditions.

Table 6b. Physiological Observations at the End of the Final Rest Cycle for Each Experimental Condition. Mean (± S.E.).

	Condition		
Variable	C	COOL	CPE
T_{re} °C	37.4 (0.1)	37.3 (0.1)*+	38.6 (0.2)*
T_{sk} °C (chest)	34.6 (0.4)	28.3 (0.9)*+	38.0 (0.1)*
T_{sk} °C (thigh)	35.5 (0.1)	36.9 (0.3)*+	37.9 (0.3)
Heart rate (bpm)	74 (2.8)	86 (4.5)*+	114 (5.0)*

* $p < 0.05$ vs. C
+ $p < 0.05$ vs. CPE

Figure 6c indicates a significant increase in sweat production for the CPE condition compared to the other trials. Figure 6d depicts the calculated mean heat removal rates by the cooling vest that were averaged over all of the 30-min rest periods. Body heat was obviously removed at a much higher rate earlier in the cooling period when skin perfusion and temperature were likely greater.

The main conclusion from this evaluation of intermittent cooling is that it can significantly improve the body's thermal balance in otherwise physically debilitating environments. Thermal balance is achieved by greatly accelerating the transfer of body heat during the required rest periods. Moreover, the required rest time is diminished, thereby significantly improving work productivity. These researchers suggested that shorter, more frequent rest/cool periods may be preferable because both the mean heat storage along with the magnitude of oscillations in T_{re} would diminish over time. The nature of the heat transfer curve also suggests the use of shorter work/rest cycles. Apparently the first few minutes of cooling are by far the most effective; primarily because heat storage, and very likely peripheral blood flow, are both varying in a regressive trend. As the temperature gradient between the skin and the cooling tubes falls, heat transfer declines. Moreover, this observation points out the complexity of the biophysical heat removal problem as well as the difficulties in accurately modeling the intermittent cooling situation.

In summary, it was found that intermittent personal cooling during rest breaks was effective in at least doubling treadmill work time. Intermittent personal cooling might reduce cost due to the reduced number of personal cooling systems required, decreased equipment design specifications, and improved work productivity. Therefore, it was concluded that intermittent cooling during rest offered an effective as well as a practical means of reducing heat storage while increasing work capacity, personal comfort, and morale.

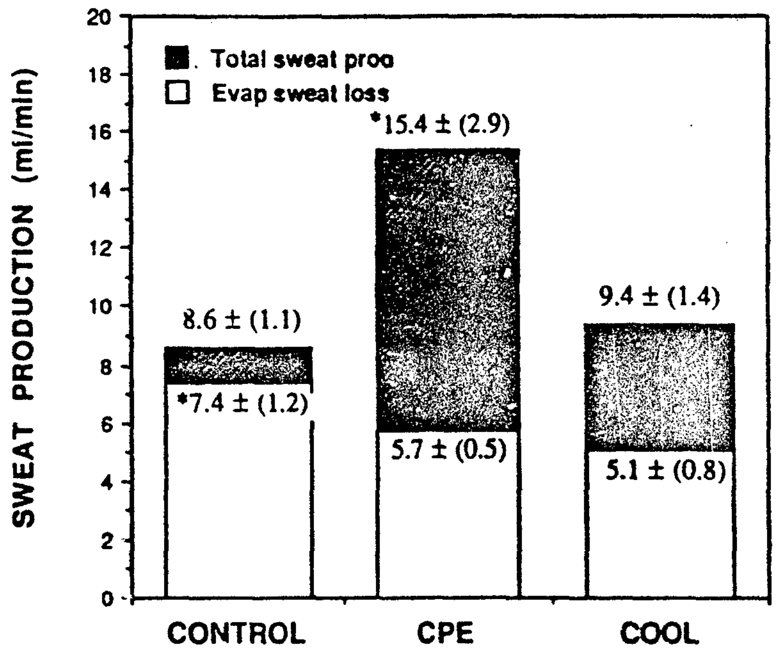


Figure 6c. Cumulative sweat rate and evaporative sweat loss response to intermittent work and rest for three experimental conditions.

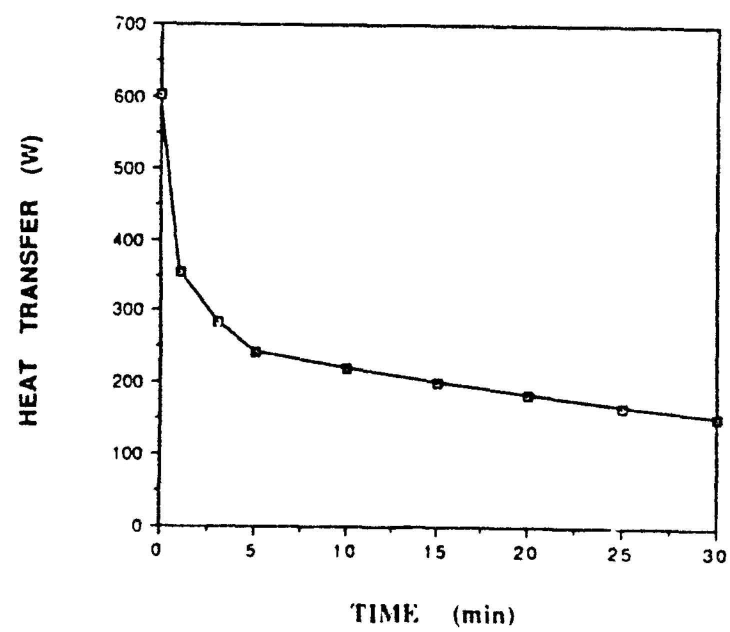


Figure 6d. Mean heat transfer with liquid cooling over time during 30 min of rest across all COOL trials.

Study #7 (Air vs. Liquid Intermittent Cooling Chamber Trials) Hot Temperatures

The purpose of Study #7 was to directly compare the physiological efficacy of intermittent liquid and air microclimate cooling for the reduction of heat stress in subjects performing heavy work under thermally stressful conditions. The subjects for this study consisted of five male and three female volunteers. The work task used for all tests consisted of walking 1.34 m/s (3 mph) at either a 3% or a 6% grade. The selected work load elicited approximately 40% of maximal aerobic capacity when the subject was wearing the protective ensemble. Subjects performed the exercise in an environmental chamber where the conditions were 38/24/44°C for T_{db}, T_{wb}, and T_{bg}, respectively. The work/rest cycles consisted of 30 minutes of walking followed by 30 minutes of sitting. Personal cooling was applied only during the rest periods. The protective clothing worn was the CDE, worn in MOPP IV configuration. The air cooling vest was that issued to U.S. Army tank crew members. Air was supplied to the vest from a U.S. Army designed cooling unit which produced 15°C air at approximately 500 liters per minute. Outlet air was directed through a flow meter for measurement purposes. The vest received 85% of the air flow with the remainder directed to the face mask. The liquid cooling system consisted of a vest with 48 m of Tygon tubing in a slip liner covering approximately 0.5 m of body surface area. Water in a mixture with 5% propylene glycol was supplied at a rate of 0.8-1.0 liters per minute to the vest. The coolant inlet temperature ranged from 10°C to 15°C and was delivered by a specially designed cooling system developed by the U.S. Air Force.

The primary focus of this research was to compare two forms of intermittent personal cooling. Data shown in Figures 7a and 7b suggest that in practice both systems performed well, at least under these conditions. In fact, there was a trend for the air cooling to attenuate oscillations in body core temperatures and heart rates slightly more effectively, relative to liquid cooling from cycle to cycle. Work duration was at least doubled, when auxiliary cooling was added. A statistical comparison was made of certain physiological parameters after the last work and rest cycles (see Table 7a). The only significant difference between the cooling perturbations was observed for thigh skin temperature. It would have been expected that the evaporative cooling component would have been slightly higher with air cooling. Surprisingly, there appeared to be little difference in the effects of the type of cooling on sweat rates or sweat evaporation (see Figure 7c).

Under the conditions studied, air and liquid cooling systems were equally effective in reducing body temperatures during intervals of rest. It was noted that air cooling was preferred by most subjects and appeared to produce drier clothing. The authors concluded that both liquid- and air-cooled systems incorporating the MICS concept have good potential for allowing military personnel to work in hot environments for extended periods while wearing protective clothing.

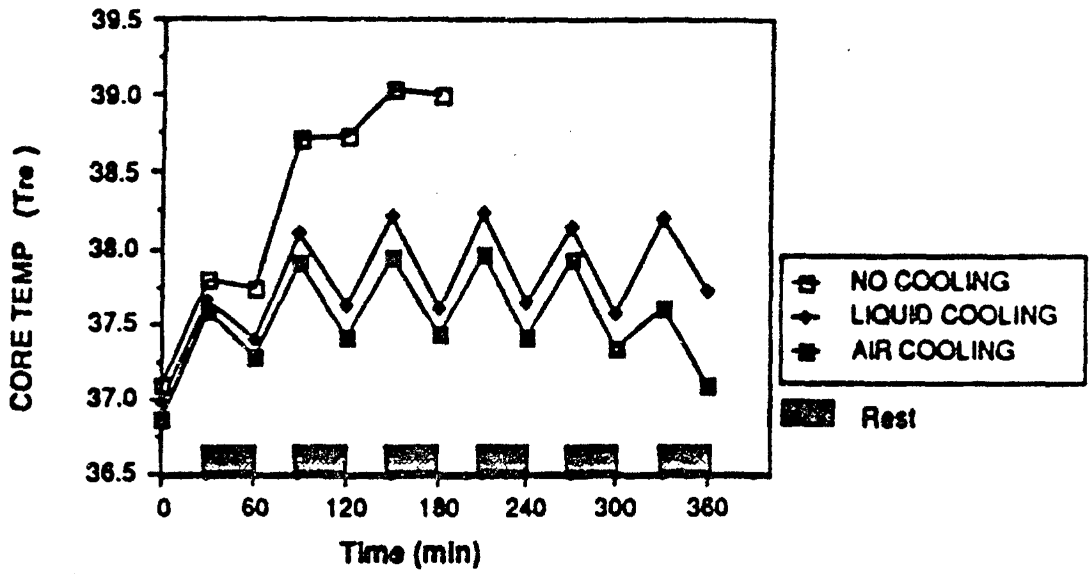


Figure 7a. Mean rectal temperature response to intermittent work under three experimental conditions.

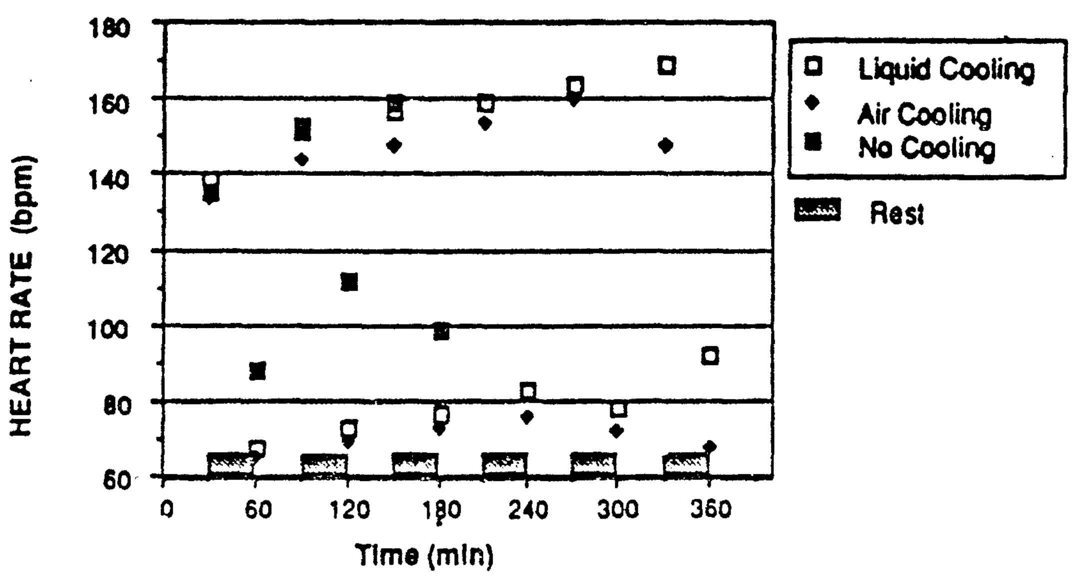


Figure 7b. Mean heart rate responses to intermittent work under three experimental conditions.

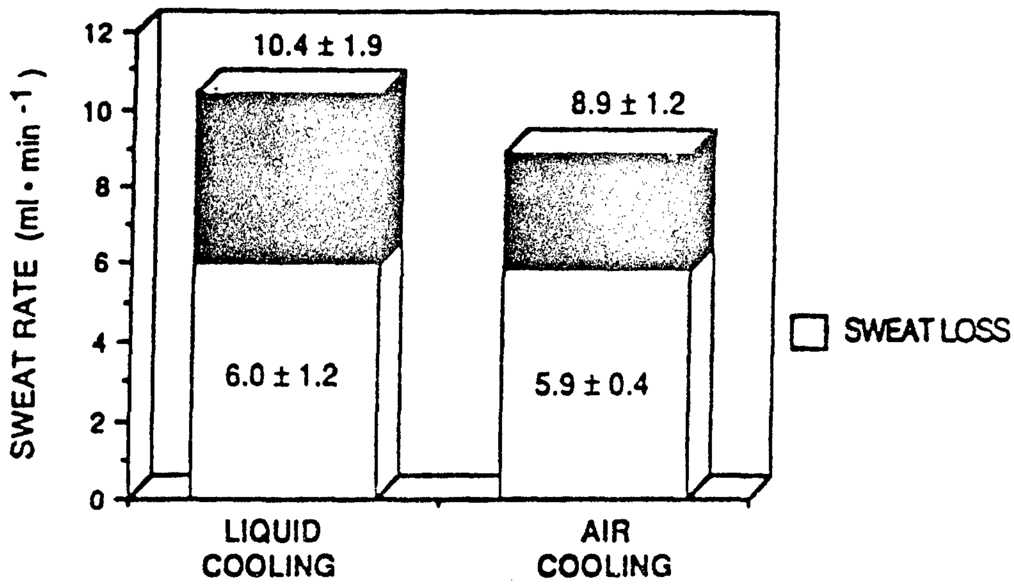


Figure 7c. Sweat production and evaporative loss for liquid and air cooling (± S.E.).

Table 7a. Final Physiological Parameters and Rating of Perceived Exertion (RPE) Observations. Mean (±S.E.) of Subjects.

	Final "Work"		Final "Resting"	
	Liquid	Air	Liquid	Air
Rectal (T_{re} °C)	38.2 (0.1)	38.0 (0.2)	37.7 (0.1)	37.4 (0.1)
Chest (T_{sk} °C)	37.4 (0.2)	36.9 (0.3)	28.3 (0.9)	29.4 (0.7)
Thigh (T_{sk} °C)	37.2 (0.3)	36.8 (0.2)	36.9 (0.3)*	35.6 (0.3)
Heart Rate (bt/min)	164 (5.8)	156 (7.5)	86 (4.5)	74 (6.7)
RPE Scale (6-20)	13.6 (1.0)	14.9 (0.8)	-	-

* Indicates significant difference between liquid and air cooling, $p < .05$.
RPE = Ratings of Perceived Exertion

Study #8 (Liquid vs. Air Intermittent Cooling Chamber Trials Warm Temperatures)

In Studies #6 and #7 the U.S. Air Force examined the use of intermittent micro-environmental cooling during the rest phase of discontinuous work and compared liquid and air personal cooling systems for heavy work in hot conditions. The purposes of Study #8 were (1) to examine the efficacy of intermittent personal cooling used during rest periods in subjects engaged in hard work in warm temperatures at a WBGT of 26°C and (2) to compare specific liquid and air cooling systems. Subjects for this experiment were 14 volunteers (12 male, 2 female). All testing was conducted in an environmental chamber at a WBGT of 26°C (28°C T_{db}, 22°C T_{wb}, and 34°C T_{bg}, respectively). Volunteers walked on an inclined treadmill at 1.34 m/sec with the grade set at a level which elicited a mean energy production rate of 430 W (1.3 L/min), representing 34% of maximal aerobic capacity. Volunteers walked for 45 min, and then rested for 15 min under the same environmental conditions as the walk, except that they sat away from the direct radiant heat source to simulate shady conditions. This work-rest cycle was then repeated until (1) volitional exhaustion, (2) heart rate (HR) exceeded 180 beats/min, (3) rectal temperatures (T_{re}) reached 39°C, or (4) 4 hr elapsed. Volunteers wore a U.S. military chemical protective ensemble (CPE) for all tests and were tested under three conditions: NO COOLING, without any supplemental cooling; LIQUID, in which subjects were cooled during rest with a liquid cooling system; and AIR, in which subjects were cooled during rest with an air cooling system. The air and liquid cooling systems were similar to those described in Study #7.

The T_{re} responses across time for the first four cycles are displayed in Figure 8a. The first work and rest cycles for each treatment were very similar. The first work cycles were identical except for the presence of the inactive cooling vests, so no differences were expected. During the second rest, the supplemental cooling began to exert some influence on T_{re}. The HR responses to each successive rest period are displayed in Figure 8b. Cooling during the preceding rest period did not generally influence HR responses at the end of the following work cycle. However, during the rest cycle, HR was significantly reduced for both types of cooling compared to rest without cooling.

Mean walk times and physiological responses at the end of the final work and rest cycles to the three conditions are shown in Tables 8a and 8b. Six subjects were able to complete 4 hr of walk/rest under the NO COOLING condition. Two subjects with a T_{re} of 39°C were stopped by investigators. Eight subjects were able to complete 4 hr or more of walk/rest under AIR, and six were able to complete 3 hr or more under LIQUID cooling conditions. No subject reached a T_{re} greater than 38.4°C for either of the cooling trials. The overall sweat production and loss rates are shown in Figure 8c. The total sweat production rate was greater for the NO COOLING trial than for the cooling trials. Absolute sweat loss was not different between trials despite different durations of exposure. Sweat loss as a percentage of sweat production was significantly higher for AIR and NO COOLING.

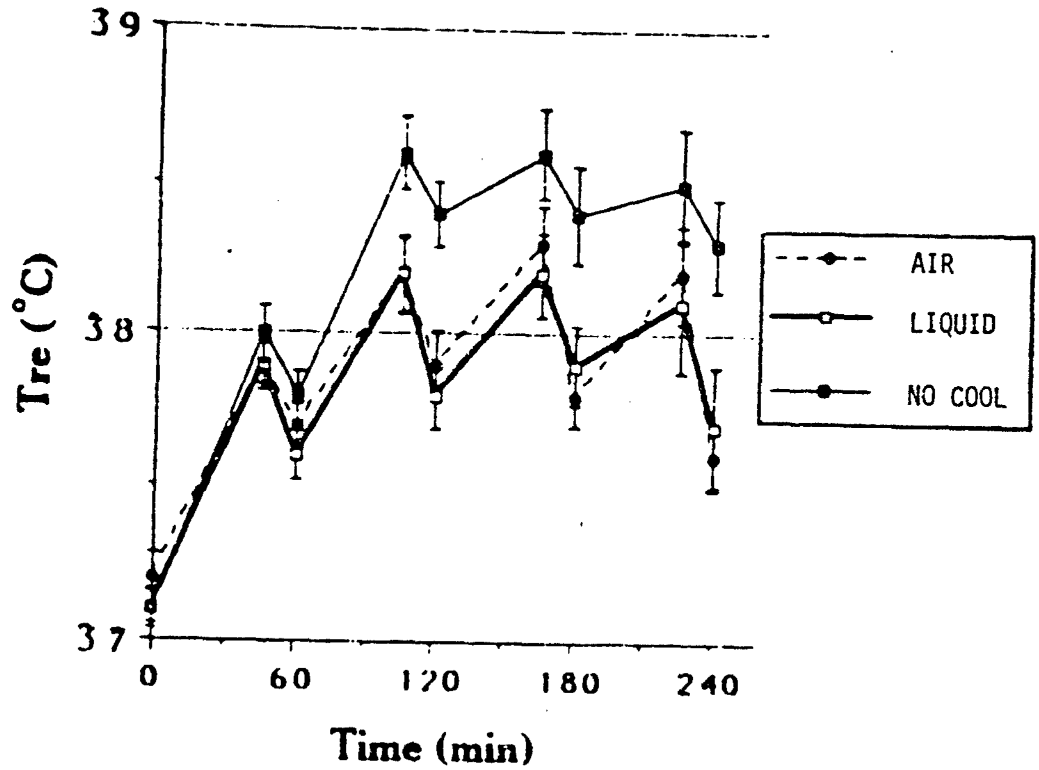


Figure 8a. Mean rectal temperature response to intermittent work under moderate environmental conditions.

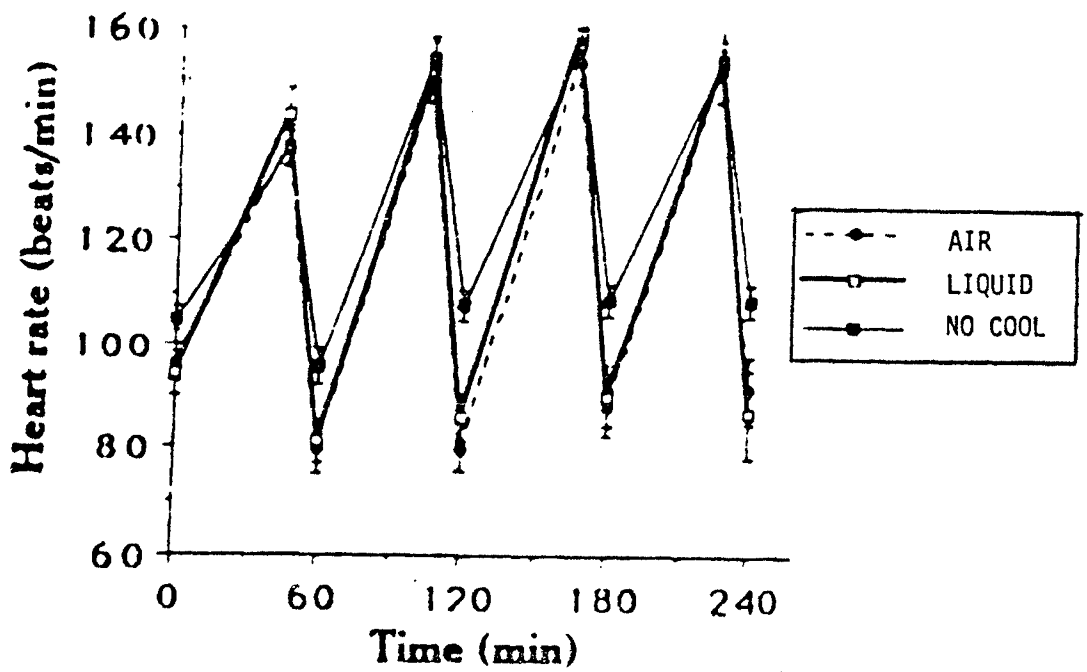


Figure 8b. Mean heart rate responses to intermittent work under moderate environmental conditions.

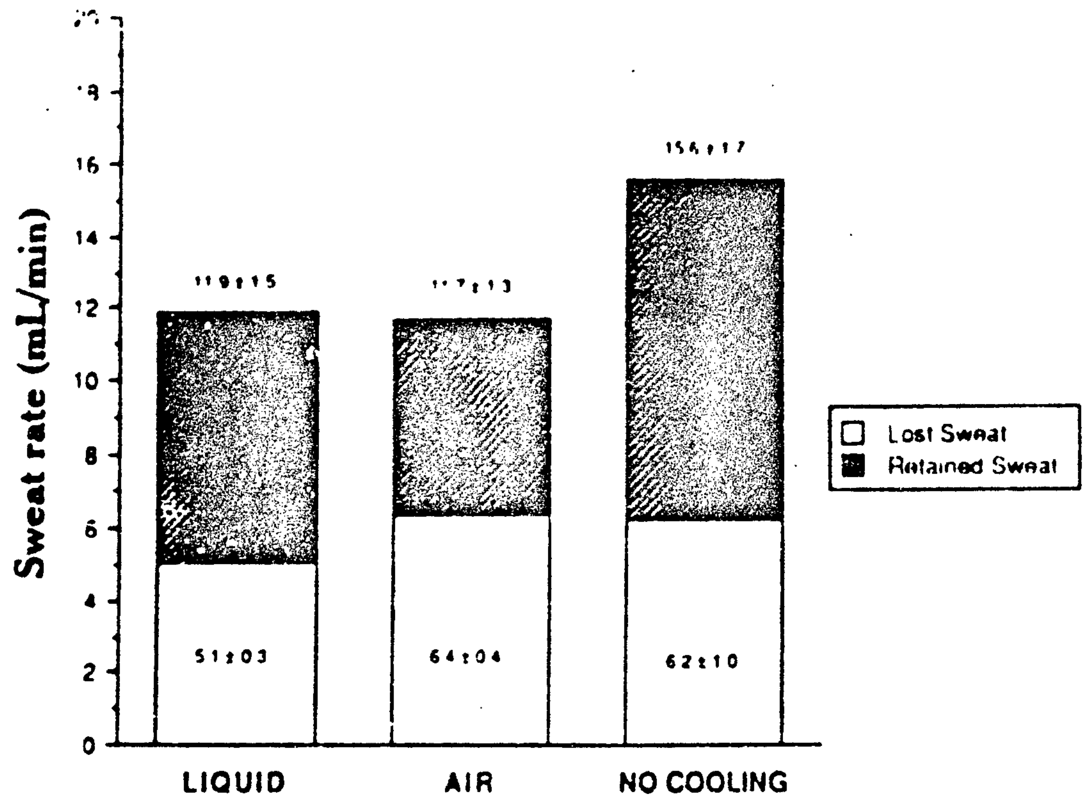


Figure 8c. Mean sweat loss (by evaporation) and sweat retained responses to intermittent work under moderate environmental conditions.

Table 8a. Physiological Response to No Cooling and Air and Liquid Cooling at the End of the Final Work Cycle (N = 14). Mean (±S.E.)

Variable/Condition	NO COOL		AIR COOL		LIQUID COOL	
Walk time (min)	135.0	(11.9)	174.0	(2.5)	156.0	(9.9)
T_{re} (°C)	38.7	(0.1)	38.3	(0.1)[a]	38.4	(0.2)[a]
Chest T_{sk} (°C)	36.9	(0.2)	36.5	(0.2)	36.9	(0.2)
Thigh T_{sk} (°C)	36.6	(0.2)	35.6	(0.2)[ab]	36.2	(0.2)
Mean T_{sk} (°C)	36.5	(0.2)	36.1	(0.3)	36.1	(0.3)
Heart rate (beats/min)	162.0	(3.4)	157.0	(4.0)	162.0	(3.4)

[a] Shows significant ($p < 0.05$) differences between the AIR or LIQUID and the NO COOL condition.
[b] Shows significant ($p < 0.05$) differences between the AIR and the LIQUID condition.

Table 8b. Physiological Response to No Cooling and Air and Liquid Cooling at the End of the Final Rest Cycle (N = 14). Mean (±S.E.)

Variable/Condition	NO COOL		AIR COOL		LIQUID COOL	
Rest time (min)	49.5	(4.1)	58.5	(4.3)	51.1	(3.3)
T_{re} (°C)	38.4	(0.1)	37.8	(0.1)[a]	38.0	(0.1)[a]
Chest T_{sk} (°C)	36.6	(0.2)	29.0	(0.7)[ab]	32.4	(0.4)[a]
Thigh T_{sk} (°C)	36.5	(0.1)	35.1	(0.2)[a]	35.2	(0.4)[a]
Mean T_{sk} (°C)	35.5	(1.0)	31.7	(0.4)[a]	33.7	(0.3)
Heart rate (beats/min)	112.0	(2.3)	91.0	(4.9)[a]	96.0	(4.7)[a]

[a] Shows significant ($p < 0.05$) differences between the AIR or LIQUID and the NO COOL condition

[b] Shows significant ($p < 0.05$) differences between the AIR and the LIQUID condition

In general, these researchers found that cooling by either AIR or LIQUID reduced physiological strain compared with NO COOLING under these conditions. After the final rest period, the AIR system appeared to be slightly more effective than the LIQUID in lowering skin temperature. It was noted that perhaps, in longer work durations, this effect might be significant, because there was a trend toward statistically significantly lower T_{re} for AIR compared with LIQUID. Thigh temperatures at the end of work were lower and chest temperatures were not lower in the cooling trials. This finding is somewhat surprising because all cooling was supplied to the upper torso. In Study #6 in which liquid cooling was compared with no cooling, also under hotter conditions (WBGT = 31 °C), intermittent liquid cooling effectively doubled work time. Although all experiments in the present study were arbitrarily stopped after 4 hr in the milder environment, AIR cooling increased mean work time by at least 28%, allowing 11 subjects to complete four work cycles, two to complete three cycles, and one to complete one work cycle. LIQUID cooling mean work time increased 16% with six subjects completing four work cycles, seven completing three work cycles, and six completing only two work cycles. The research team suggested that the smaller increase of work time in the present study may be attributed to the premise that, under (other) hotter conditions, work without supplemental cooling was often limited by high rectal temperatures. At these lower temperatures, fatigue, rather than the T_{re}, seemed to be limiting. The study extended the findings of previous USAF work by showing that the two cooling systems provided similar physiological responses in subjects performing heavy work under moderate conditions. Consistently, in all of the previous studies, under different combinations of work ratios and environment, air cooling produced a slightly better physiological response than liquid cooling. Based on the results of the present study, the advantages of intermittent personal cooling appear to diminish as ambient temperatures are reduced.

Study #9 (Impermeable Suit Cooling Chamber Trials)

Included in Study #9, two different CWD (groundcrew) "compressed air cooling" suits were evaluated for reduced thermal stress compared to the standard CDE in use. The two ensembles tested were classified according to manufacturer, i.e., Bullard and Encon CAC (compressed air cooling) suits. Both garments are completely impermeable (as opposed to the standard CDE) to both liquids and vapors. The Encon CAC suit may be used in two operational modes; either tethered to an air source for (vortex) chilled air delivery, or wearing a backpack blower that delivers ambient air at a rate of 13.4 cfm and weighed 18.4 lb (36.3 lb for the total system). The assembly incorporated "much heavier material" and an integral (to the suit) filter blower (2.8 cfm) air distribution system. (Total weight of system = 24.2 lb.) Alternatively, it too could be connected to a similar air supply employing the integral vortex chiller (tethered mode).

The experimental protocols were initially attempted with six subjects. Protocol I was designed to simulate rapid runway repair (RRR) work loads. The subjects donned each of three CD ensembles on separate occasions: (1) the standard groundcrew CDE (Condition C); (2) the Encon suit (condition E); or (3) the Bullard suit (condition B). Subjects then walked on a treadmill at 3.3 mph and 5% grade (= 400 kcal/hr) under environmental conditions of 32°C T_{db}, 22°C T_{wb}, and 37°C T_{bg}. The wind speed was observed to be quite low. A work/rest ratio of approximately 30/26 was incorporated. This protocol apparently equated to three 10-min work bouts interspersed with two 3-min rest periods and followed by a 20-min rest period. Under conditions E and B, vortex cooled air was supplied to the subject during the 20-min rest period, while the ambient air blowers were functioning during the rest of the time (B+C only). Protocol II differed in several ways. First, six alternating 10-min work/3-min rest periods were used, while after the 6th and 12th work bout, a 10-min rest period followed. Only the suit (condition B) was tested here and vortex-cooled air was supplied throughout the entire test. Instead, a second "cooling" trial was accomplished by having the subjects wear a liquid cooling system under the CDE. This was apparently a commercially produced system, but was not further described in the original report. Moreover, it was noted that some "supplemental" evaluations were also accomplished using Protocol II ("high flow" (HF) vortex cooling) instead which delivered -10°C air to the wearer at 12 cfm. This change was suggested to be an improvement of 2-fold in flow rate reported along with a decrease of 10°C in inlet temperature over the standard vortex system. However, both flow rates and inlet temperatures were omitted from the report.

A review of Table 9a demonstrates that neither CAC suit system offers any physiological advantage over the standard CDE. Interestingly, the recovery after achieving a T_{re} of 39.0°C is not accelerated by the application of vortex cooling (w/CAC suit) as compared to the CDE trial where the subject recovered in front of an external fan (Figure 9a). In fact, the CAC suits reduced the mean tolerance time by 36%. An additional observation was noted that the subjects experienced "air-hunger" when wearing the suit. The low air flow rate (2.87 cfm) here propagated an increase in [CO_2] within the headpiece to as high as 3.5%. In Protocol II (Table 9b), when continuous vortex chilled air cooling was applied, there was no improvement over the control trial (condition C). However, there was considerable improvement in hydration levels; sweat rates were reduced approximately 60% with moderate improvement in sweat evaporation efficiency (percentage). Interestingly, these improvements were not as great as those observed with liquid cooling (Table 9b). Finally, in the supplemental trials where "high flow" vortex cooling was tried, little physiological advantage was noted (Figure 9b). Work tolerance times here were similar to controls.

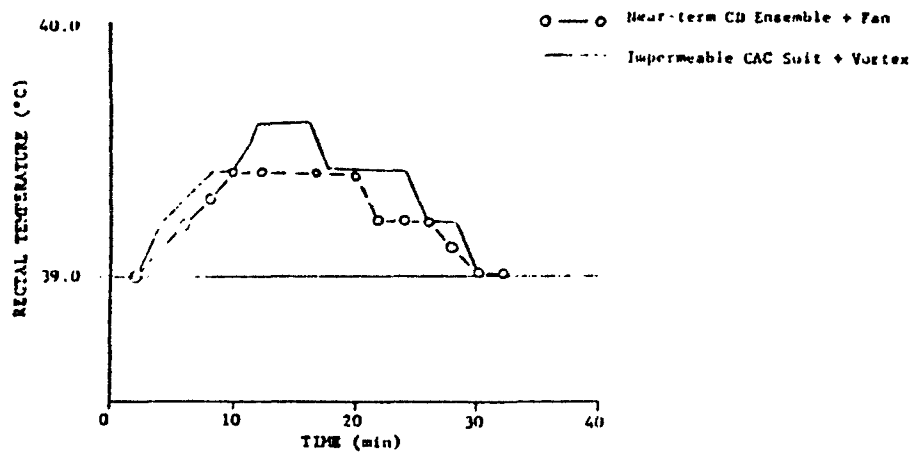


Figure 9a. Duration of rectal temperature overshoot.

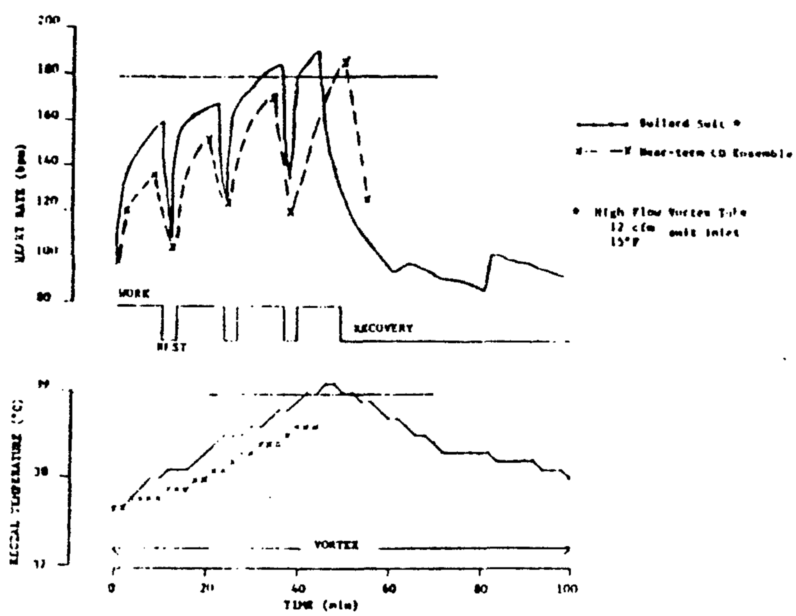


Figure 9b. Physiological responses of one subject to work in the heat.

Table 9a. Protocol I Test Results

	Near-term Ensemble	Encon Suit	Bullard Suit
	N=5	N=4	N=3
Rate of rise in rectal temp. (°C/h)	1.4	1.8	1.6
Rate of rise in mean skin temp. (°C/h)	3.8	5.5	6.0
Heart rate at end of work bout:			
#1	128.0	140.0	149.0
#2	144.0	155.0	171.0
#3	158.0	169.0	183.0
Sweat rate (g/h)	660.0	590.0	570.0
% Sweat evaporated	40.0	31.0	48.0
Duration of T_{re} overshoot (min)	30.0	30.0	30.0
Tolerance time (min)	76.0	49.0	48.0

Table 9b. Protocol II Test Results

	Near-term Ensemble	Bullard Suit	Liquid-Cooled Vest
Ensemble weight (kg)	7.0	11.0	13.5
Subjects tested	5.0	5.0	3.0
Rate of rise in rectal temp. (°C/h)	1.7	1.5	0.5
Heart rate at end of work bout:			
#1	124.0	143.0	127.0
#2	141.0	157.0	146.0
#3	155.0	168.0	146.0
Sweat rate (g/h)	1400.0	600.0	720.0
% Sweat evaporated	25.0	31.0	42.0
Duration of T_{re} overshoot (min)	No Data	30.0	No Data
Tolerance time (min)	50.0	51.0	>170.0

Overall, the investigators found little if any advantage to the CAC system approach. In fact, many physiological and physical concerns were noted concerning the practical implementation of the CAC concept. It is very important to point out the fact that these suits impose an increased weight (and bulk) on the subject. Accordingly, this additional burden increases the energy expenditure (and metabolic heat production) required to do the same tasks. Furthermore, the administration of very low temperature air cooling may be somewhat counterproductive by eliciting a peripheral vasoconstriction which would decrease heat flux from the body core.

COMBINED COOLING STUDIES

Study #10 (Continuous Air Cooling, Warm, and Hot Environments)

Study #10 was an attempt to further increase the capacity for heat removal and at the same time decrease cumulative fatigue and discomfort by the use of ambient air cooling during work periods, in addition to the conditioned air cooling during rest periods. The subjects for this series of tests consisted of civilian and military volunteers. The task used for all test batteries described in this paper consisted of walking 1.34 m/s (3 mph) at either a 3% or a 6% grade with intermittent rest periods. The selected work load elicited approximately 40% of the subject's maximum aerobic capacity. Subjects performed the intermittent exercise in an environmental chamber where conditions were described in degrees Celsius by measures of dry bulb (T_{db}), wet bulb (T_{wb}), and black globe (T_{bg}) as either warm (n=8) or hot (n=7). These values were as follows: warm conditions = 28, 22, 34°C; and hot conditions = 38, 26, 44°C, respectively. The ratio of work to rest was 3:1 for warm conditions and 1:1 for hot conditions. From an absolute time standpoint the work/rest ratio equated to 45:15 min and 30:30 min, respectively. The following three experimental perturbations were employed (subjects served as their own controls): (1) no personal cooling during work or rest (no cooling, NC), (2) conditioned air cooling during rest periods only (intermittent cooling, IC) and (3) ambient air cooling during work, plus conditioned air cooling during rest (continuous cooling, CC). Criteria for stopping a test were: (1) rectal temperature = 39.0°C, (2) a sustained max heart rate as determined during a VO_{2max} test, (3) volitional fatigue, (4) judgment of the medical monitor, or (5) a total trial time of 240 min. The protective clothing worn was again the military CDE MOPP IV configuration. The air-cooled vest was developed by the U.S. Army primarily for use with tank personnel and has been cited previously in this report (studies #7 and #8). An open circuit system was used to deliver 18 cfm at approximately 20°C to subjects during rest periods in the air-cooling trials. Again, an accommodation was made to divert 3 cfm away from the vest directly to the face mask. The same system was used to deliver ambient (not conditioned) air during work cycles in the CC trial in addition to the conditioned air during rest periods.

Warm Conditions: In the NC trial, total work time was 130 minutes. The addition of intermittent air cooling during rest (IC) significantly increased work time to 159 min, while ambient air cooling during work (CC) allowed subjects to work for a mean of 163 min. Mean rectal temperatures (T_{re}) at the end of each work interval for all three cooling conditions are shown in Figure 10a. By work and rest cycle 2, T_{re}, during NC, was significantly higher than during either CC or IC. Mean Heart Rates (HR) (Table 10a) at the end of work cycles did not differ. However, the HR response in the NC condition was significantly higher during rest cycles 2, 3, and 4 than when conditioned air cooling was applied (IC, CC). Values for mean skin temperature illustrated in Fig. 10b were significantly lower in the continuous cooling condition than in either NC or IC for work cycles 2, 3, and 4. During rest intervals, mean skin temperatures for the NC condition were also significantly higher.

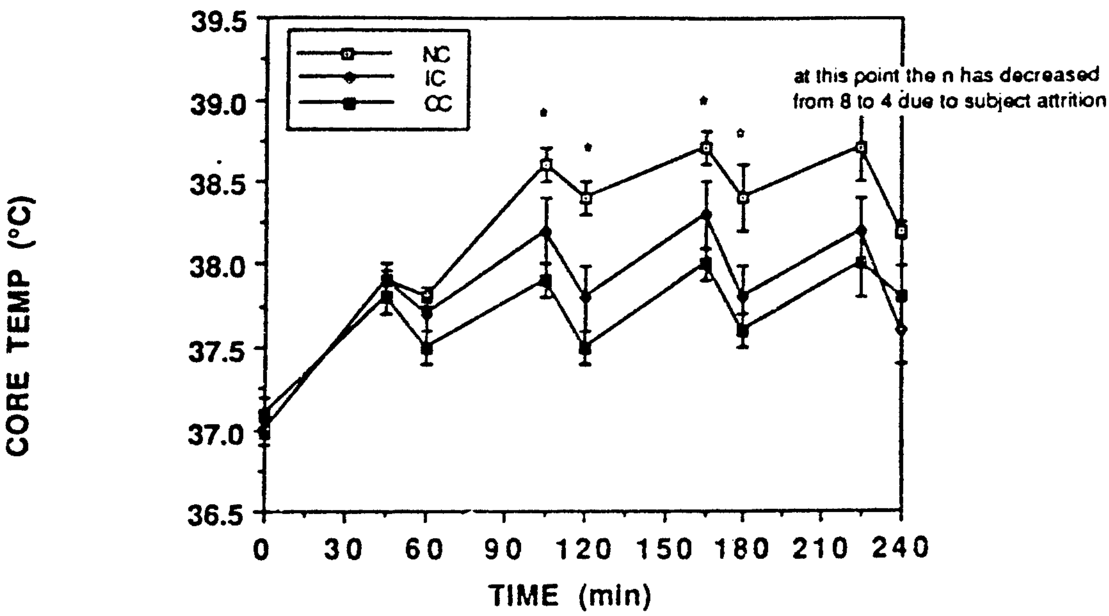


Figure 10a. Mean body core temperature responses to each experimental condition during work and rest in a warm environment.

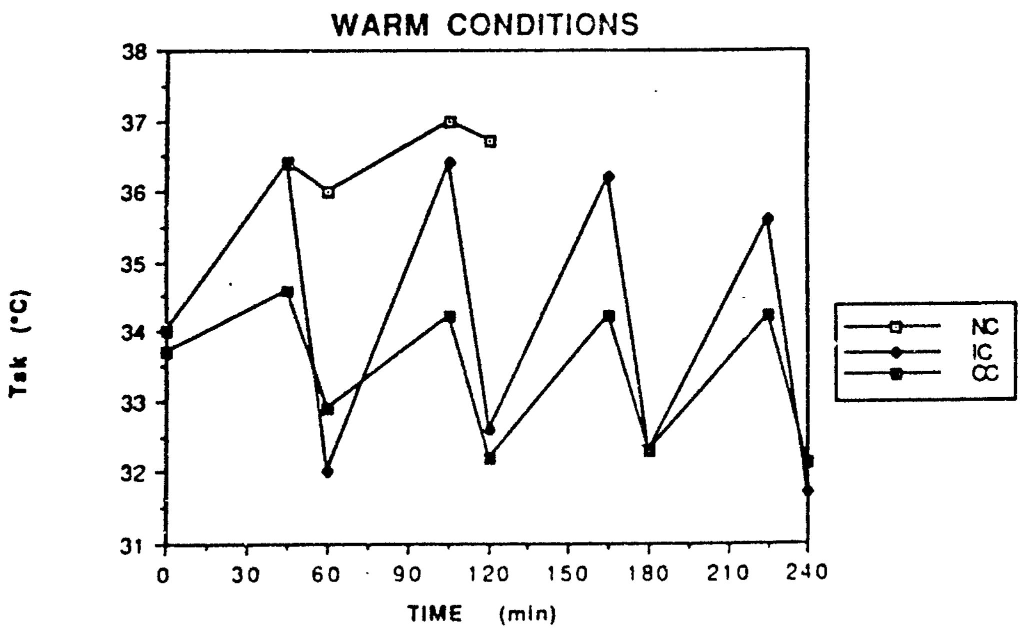


Figure 10b. Mean skin temperature responses to each experimental condition during work and rest in a warm environment.

Table 10a. Heart Rate at End of 45-Min Work and 15-Min Rest Cycles in Warm Conditions. Mean (± S.E.).

	Time (Min)								
	0	45	60	105	120	165	180	225	240
NC	102 (2)	144 (5)	93* (4)	154 (6)	109* (4)	161 (5)	110* (2)	161 (5)	108 (6)
IC	99 (5)	144 (5)	79 (4)	154 (5)	79 (5)	160 (6)	92 (8)	160 (6)	109 (7)
CC	98 (6)	136 (6)	78 (5)	139 (7)	84 (6)	140* (8)	81 (8)	140 (8)	85 (9)

* Significantly different ($p < .05$) from other two conditions

Table 10b. Thermal Comfort (TC) and Ratings of Perceived Exertion (RPE) at the End of 45-Min Work Cycles in Warm Conditions. Mean (± S.E.).

	1 TC	RPE	2 TC	RPE	3 TC	RPE	4 TC	RPE
NC	5.25(.21)	12.9(1.2)	5.65(.26)	15.0*(1.5)	5.82(.35)	15.9*(2.0)	5.23(.37)	16.5*(1.0)
IC	5.17(.19)	13.2(.7)	5.57(.18)	14.25*(.6)	5.75(.29)	14.78(.68)	4.7 (.41)	14.6 (.8)
CC	4.69(.21)	12.5(.5)	4.87*(.35)	13.25*(.5)	5.12*(.4)	14.12(1.0)	5.12(.49)	14.4 (1.1)

* Significantly different ($p < .05$) from other two conditions

Moreover, significant differences in patterns of rectal temperature, heart rate, and mean skin temperature over time during both work and rest cycles were observed due to the greater increases in these variables in the NC scenario. Further, analysis resulted in significant differences between the two cooling conditions for the patterns over time. The implication of these results is that CC was more effective than IC in reducing cumulative heat storage over time. Also, HR values during work and rest cycles were consistently higher in IC than in CC. Mean skin temperatures over time were not different between CC and IC during rest because conditioned air was applied in both cases. Sweat production (SP) rates were significantly lower for the CC condition than for both IC and NC (Fig. 10c). Although sweat evaporation (SE) rates for both cooling methods were similar, the percentage of sweat produced that was evaporated (SE/SP) was significantly greater for the CC condition than for either of the other two conditions. Subjective ratings for thermal comfort taken during work periods were significantly lower during CC trials than during IC and NC trials for cycles 2 and 3 (Table 10b). RPE during the CC trial was also significantly below those taken during the IC trial during the second work cycle and significantly lower than NC ratings during work cycles 2-4.

Hot Conditions: A mean total work time (74 min) in the NC trial was increased significantly to 116 min during the intermittent cooling and continuous cooling trials. Rectal temperature in the NC trial was significantly higher than IC or CC by the first rest cycle, and remained so during both work and rest until the termination criterion was reached (Fig. 10d). Heart rate responses during work cycles appeared to differ less between the experimental perturbations. Unfortunately, during this trial, forearm and calf temperatures were not recorded for all subjects. However, comparisons of thigh and chest skin temperature for each condition are illustrated in Figure 10e. During work cycles, the NC chest temperature is not different from the intermittent cooling condition. Both of these levels are higher than the CC condition rest cycles; NC chest temperature is significantly higher than either CC or IC due to the application of conditioned air, and CC chest temperature is higher than the IC chest temperature. The difference in thigh temperature among the three conditions was not as extreme since the air from the cooling vest is not blowing directly on this area of the body. Using a three-way ANOVA, these researchers found significant differences in patterns of rectal temperature and skin temperature over time during both work and rest cycles. The response for heart rate over time showed similar characteristics with no significant differences between the values for CC and IC (Table 10c). Thermal comfort (TC) ratings (Table 10d) were significantly lower for CC than for IC during each work cycle. RPE values tended to be lower in the CC condition, although this difference was not always significant. Analysis of sweat rates showed that SP for the CC condition was significantly lower than for NC, and was lower, but not significantly, than IC values. SE rates were similar for all three cooling methods, however, percent evaporation was again significantly greater for CC than IC and NC (Fig. 10f).

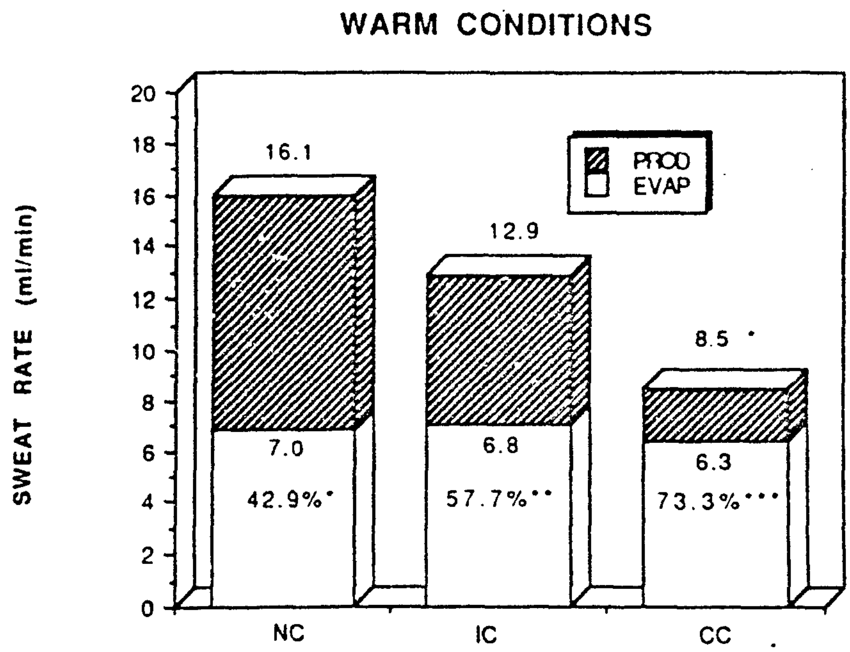


Figure 10c. Sweat production, evaporation, and percentage of sweat produced which evaporated for each experimental trial (Work:Rest = 45:15 min).

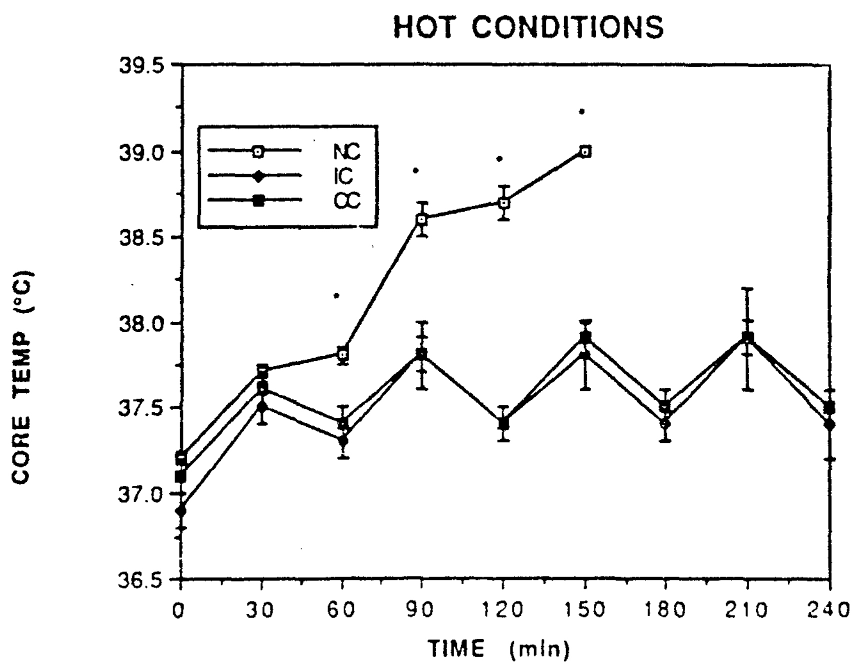


Figure 10d. Mean body core temperature responses to each experimental condition during work and rest in a hot environment.

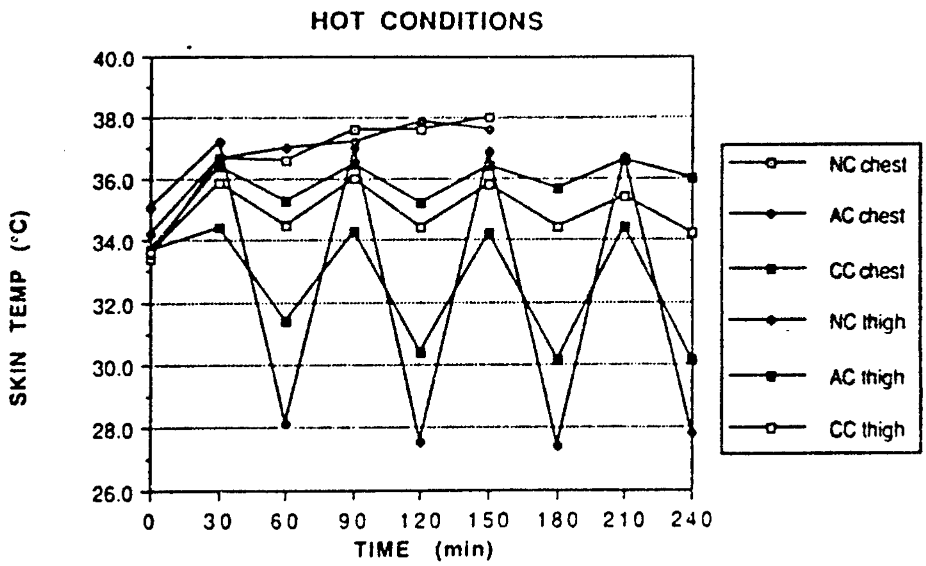


Figure 10e. Mean chest and thigh temperature responses to each experimental condition during work and rest in a hot environment.

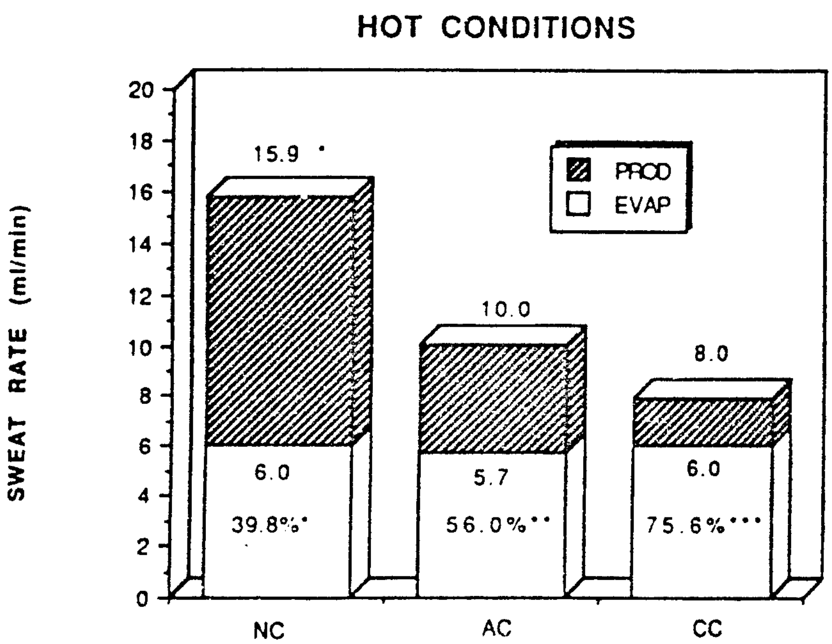


Figure 10f. Sweat production, evaporation, and percentage of sweat produced which evaporated for each experimental trial (Work:Rest = 30:30 min).

Table 10c. Heart Rate at the End of 30-Min Work and 30-Min Rest Cycles in Hot Conditions. Mean (± S.E.).

	Time (Min)								
	0	30	60	90	120	150	180	210	240
NC	102 (3)	135 (5)	93* (5)	152* (5)	113* (8)	160 (14)			
IC	93 (3)	126 (6)	66 (5)	140 (7)	65 (3)	142 (9)	69 (5)	143 (11)	75 (9)
CC	92 (6)	123 (2)	70 (6)	131 (3)	74 (9)	135 (4)	72 (6)	138 (6)	79 (7)

* Significantly different ($p < .05$) from other two conditions

Table 10d. Thermal Comfort (TC) and Ratings of Perceived Exertion (RPE) at the End of 30-Min Work Cycles in Hot Conditions. Mean (± S.E.).

	1 TC	RPE	2 TC	RPE	3 TC	RPE	4 TC	RPE
NC	–	12.0(.4)	–	13.6(.7)	–	15.5(1.7)	–	–
IC	5.6(.18)	12.4(.8)	5.8(.2)	13.4(.5)	5.8(.14)	14.0(.5)	5.8(.19)	14.1(.9)
CC	4.8*(.2)	11.6(.6)	5.0*(.2)	12.2*(.7)	5.1*(.2)	12.9*(.9)	4.8*(.25)	12.5(1.1)

* Significantly different ($p < .05$) from other condition(s)

Overall, in both environmental settings, IC and CC significantly increased work times and appeared to decrease thermal strain, as is demonstrated by lower T_{re} and HR during work and rest, compared with NC responses. In the warm environment there was a significant trend for subjects to better maintain "thermal equilibrium" over time during CC than in IC: that is, to minimize cumulative heat gain across the trial. CC also appeared to allow a more complete physiological recovery during rest than did IC, even though identical conditioned air was supplied during rest in both cases. It was suggested that this inconsistency is probably due to lower T_{re} and HR values that were observed prior to starting each rest cycle in the CC trial. The hotter (38°C) ambient air delivered during work did not appear to give as much physiological relief as the warm (28°C) air. However, the subjective, or psychological, relief was still evident here as is indicated by improved TC and RPE ratings. Furthermore, in calculating the sweat evaporation to production ratio (E/P), the E/P ratios seen in this study (averaged for both temperatures) were 74% for CC, 57% for IC, and 41% for NC and appear to correspond well to the subjective ratings assigned under each condition.

These results imply a greater degree of overall comfort for the subjects when they received ambient air cooling during work cycles. The researchers noted that subjects generally commented that they were "more comfortable," and "not working as hard" when they received ambient air during work in addition to conditioned air during rest (CC), in both warm and hot environments. It was suggested that the psychological advantage may be as great as the physiological benefit of CC especially under hot conditions. Moreover, ambient air cooling during work provides additional toxic agent protection by producing a modest overpressure within the CD ensemble.

Study #11 (Continuous Air Cooling Hippack Chamber Trials)

Study #11 describes the system and physiological testing of a very lightweight, human-mounted air cooling approach. An ambient air cooling unit which can provide adequate clean air was developed and tested in a controlled thermal chamber. Study #9 (this report) first evaluated this concept of "continuous cooling" by simulating the ambient air flow and not wearing an actual cooling unit. The cooling unit is composed of a battery-powered vacuum blower, battery set, air plenum, control panel, three C-2 filters, and support frame. This compact "belt pack" unit weighs approximately 8.5 pounds with battery and provides 12 cfm filtered ambient air through a U.S. Army developed air vest (10 cfm to the body and 2 cfm to the face). The unit is energized by a 24 Volt/2.2-ampere battery activating a one-stage blower which draws ambient air through three canister filters for up to 3 hours of continuous operation. This system is ergonomically balanced on the individual's hips with shoulder supports and does not appear to interfere with normal job performance. The unit may be used independently or in conjunction with the MICS approach. The seven subjects used for the series of tests were military volunteers. Subjects wore the air vest over a cotton T-shirt and under the battle dress uniform and the military chemical defense ensemble (MOPP IV configuration). The physical work consisted of walking on a treadmill at 3 miles per hour (4.8 kilometers per hour) at a 3% to 6% grade, which elicited approximately 40% of subjects' VO_{2max}. Subjects performed either intermittent or continuous exercise in a thermally controlled chamber under warm conditions (32°C, 40% RH) until reaching limits of rectal temperature (T_{re}) 39.0°C, heart rate (HR) 180 bpm, or volitional fatigue.

For intermittent work, three experimental conditions were employed: (1) No Cooling (NC): Subjects completed the intermittent exercise periods without any personal cooling during work or rest cycles, (2) Intermittent Cooling (IC): Subjects received conditioned air cooling during rest periods, but walked on the treadmill without ambient air cooling, and (3) Continuous Cooling (CC): Subjects wore the operational ambient air cooling unit during work periods and also received conditioned air cooling during rest periods. In this intermittent work scenario, four cycles of 40 min work (450 Watts) and 20 min rest were attempted at each condition. Subjects received 18 cfm of conditioned air (15.5°C-18.3°C) during 20 min of rest for the IC and CC conditions. In a second set of experiments during continuous work, subjects walked on the treadmill continuously until reaching one of the termination criteria specified previously. Two experimental conditions were observed, (1) no personal cooling (NC): ambient air cooling unit not employed, (2) ambient air cooling (AC): again subjects carried a functioning ambient air unit.

During the intermittent work scenario where subjects attempted 4 hours of work/rest cycles, all seven subjects completed at least 80 minutes in the NC trial. Analysis of these data indicated that individuals who received cooling in the IC and CC trials performed better than in the NC condition relative to the physiological measures of heart rate, skin temperature, core temperature, and heat storage. Increases in rectal temperature and mean skin temperature observed over the first three work periods tended to be greater during IC than CC (See Figs. 11a and 11b). Although there were no differences in heart rate during the work cycles, the average heart rate during rest cycles with CC was lower than for IC (See Fig. 11c). Heat storage values were not statistically different between CC and IC during 140 minutes of intermittent work; however, the data suggest that physiological differences may exist since CC values tended to be consistently lower than IC measurements (See Fig. 11d). Using ambient air during work cycles helped to keep skin temperature lower than under the IC and NC conditions. Sweat production rates (SP) were significantly lower for CC and IC than for NC; the rate for CC was lower than for IC (Fig. 11e). The sweat evaporation rate for CC was higher than for IC and NC.

During 50 minutes of continuous work, use of ambient air cooling (AC) resulted in a significantly lower increase in heat storage (Fig. 11f). Mean skin temperature (Fig. 11g) was also significantly higher in the no cooling (NC) trial. AC had a significant effect on lowering thermal comfort ratings (TC), which was evident even at the 10-minute point (See Fig. 11h). Sweat production rates (SP) were not different for AC and NC. However, there was a significant difference in sweat evaporation (SP) and percent of sweat evaporation (Fig. 11i).

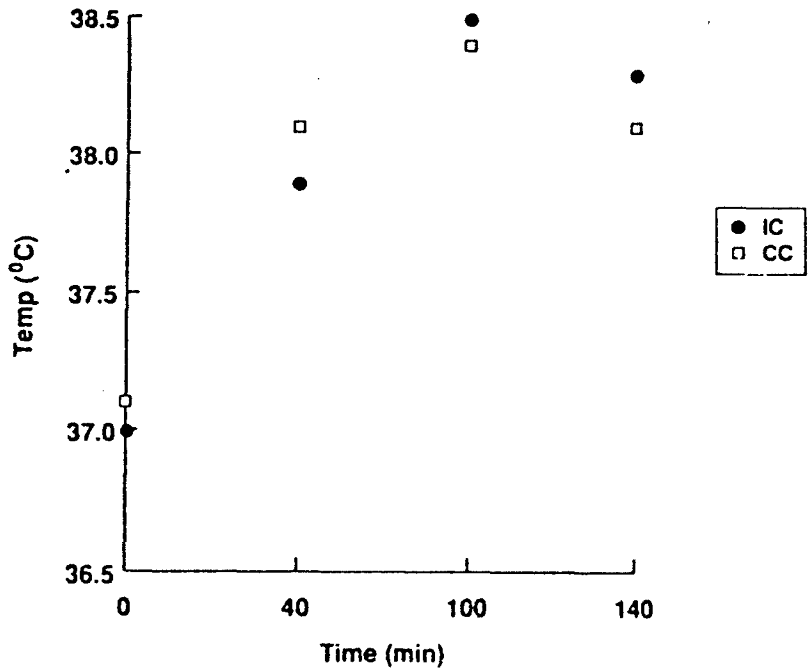


Figure 11a. Rectal temperature responses at the end of each work cycle with intermittent cooling (IC) or continuous cooling (CC).

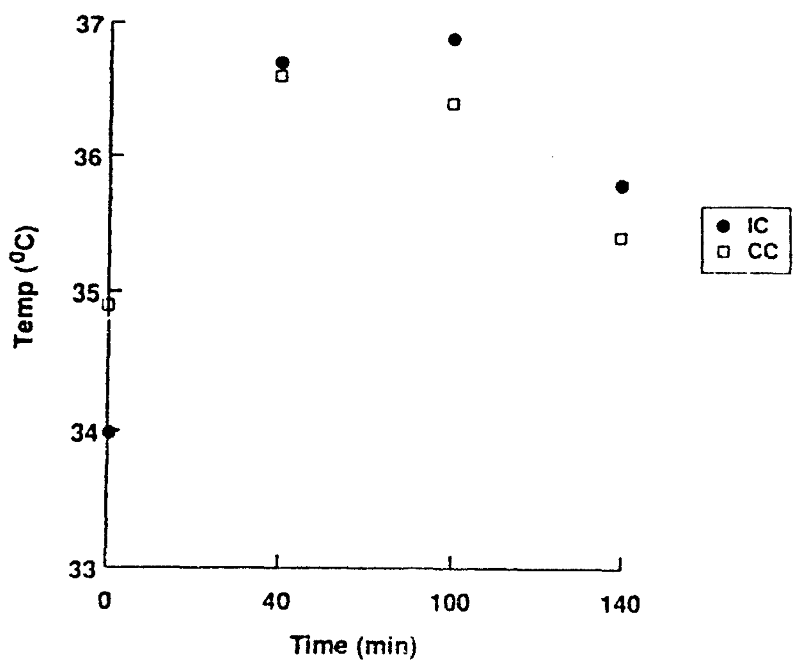


Figure 11b. Mean skin temperature responses at the end of each work cycle with intermittent cooling (IC) or continuous cooling (CC).

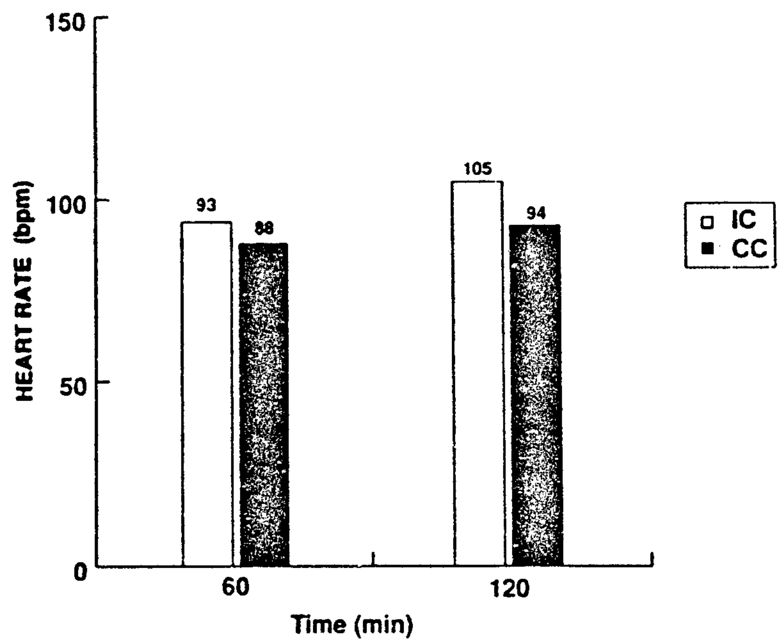


Figure 11c. Heart rate responses at the end of the first two rest cycles with intermittent cooling (IC) or continuous cooling (CC).

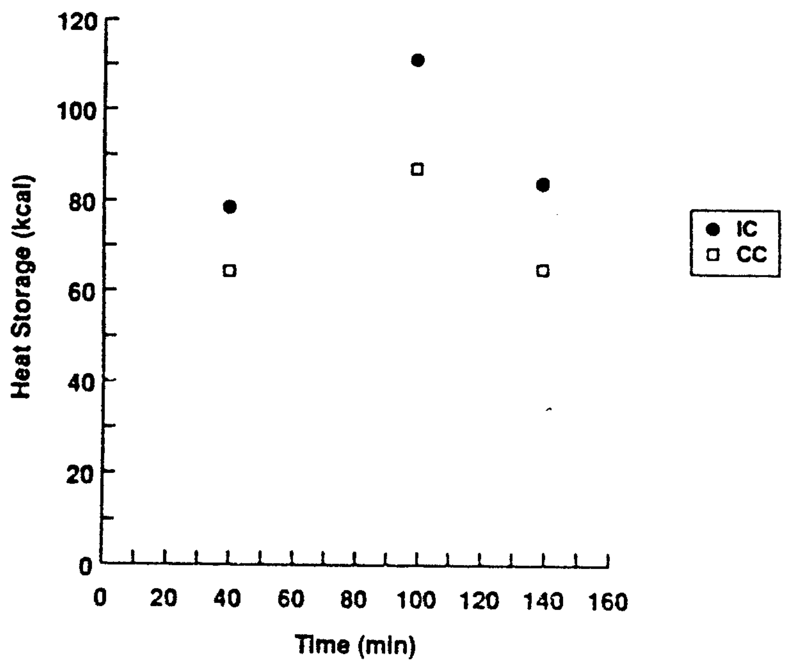


Figure 11d. Calculated heat storage values at the end of work cycle for intermittent cooling (IC) or continuous cooling (CC).

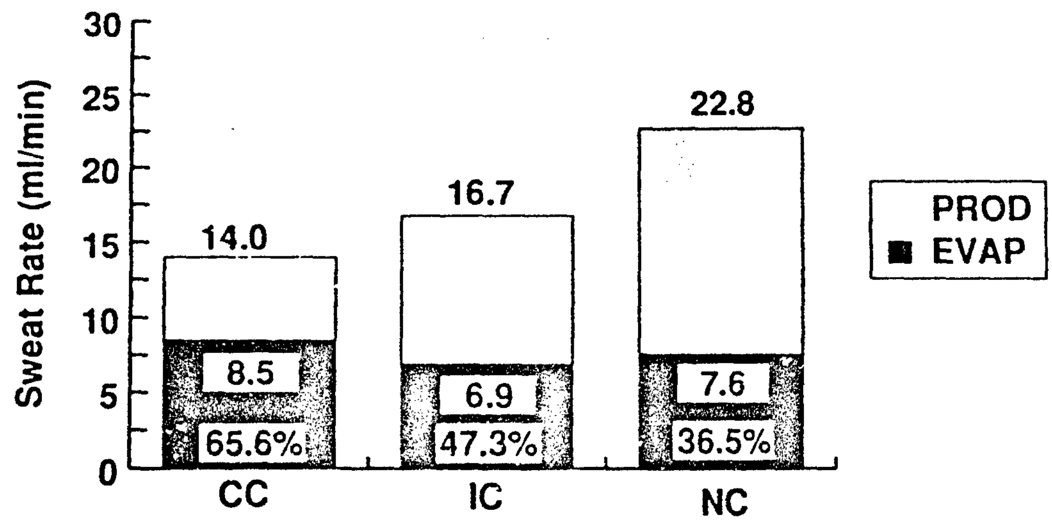


Figure 11e. Sweat production, evaporation, and percentage of sweat produced which evaporated for each experimental trial.

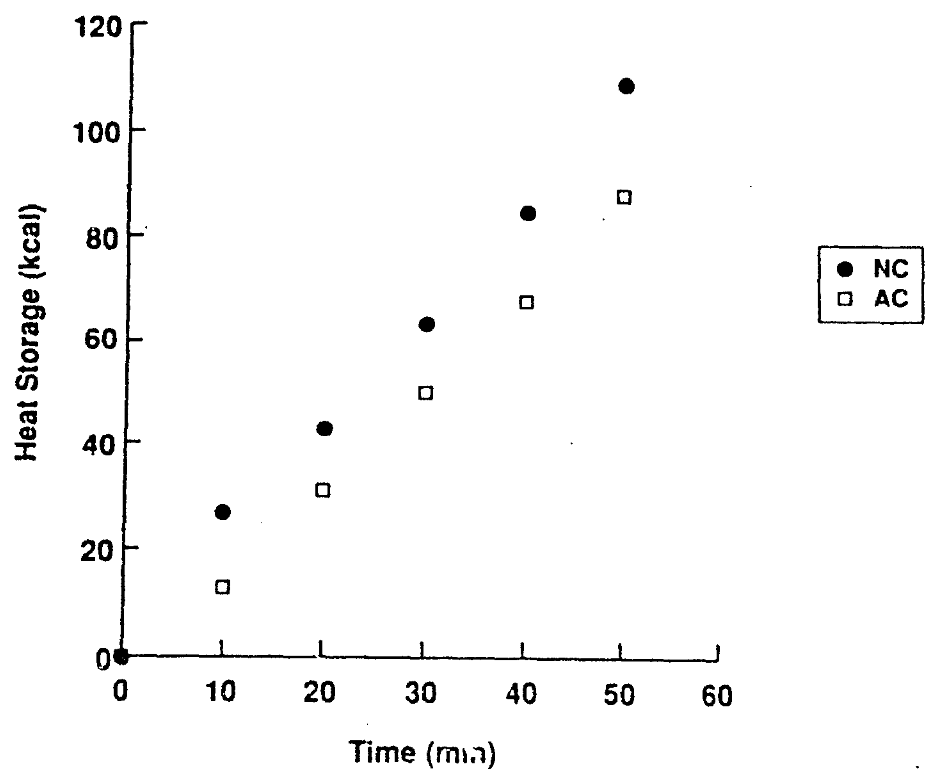


Figure 11f. Calculated heat storage values during continuous work. AC = Ambient Air Cooling; NC = No Cooling.

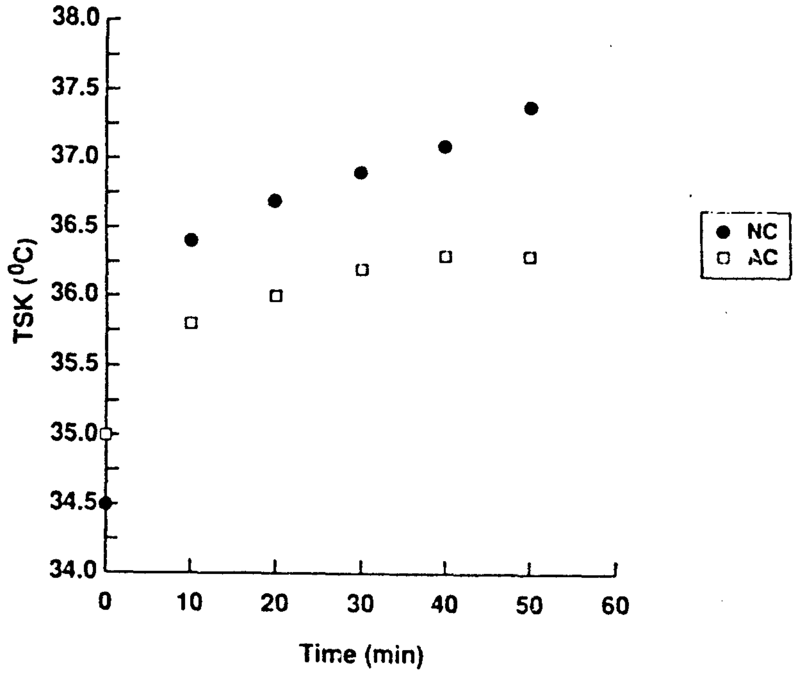


Figure 11g. Mean skin temperature responses during continuous work. AC = Ambient Air Cooling; NC = No Cooling..

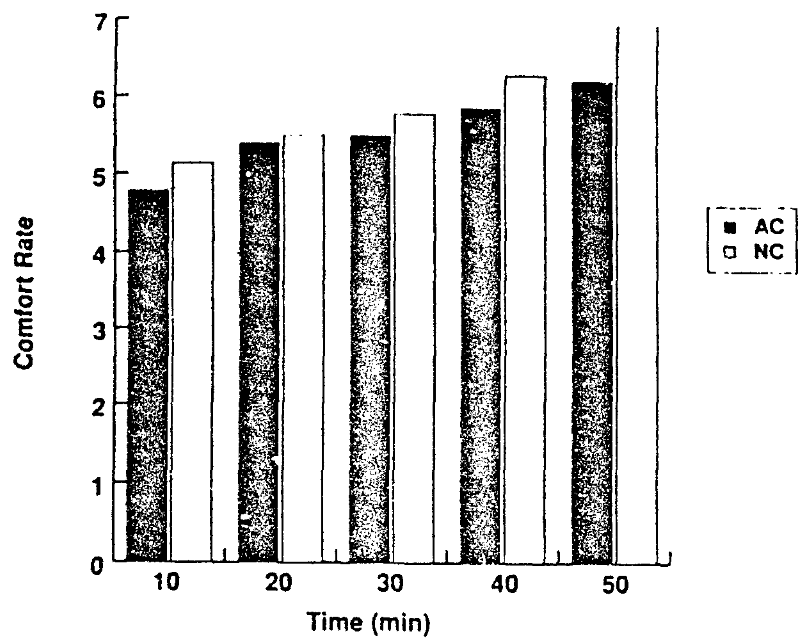


Figure 11h. Thermal Comfort ratings during continuous work. AC = Ambient Air Cooling; NC = No Cooling.

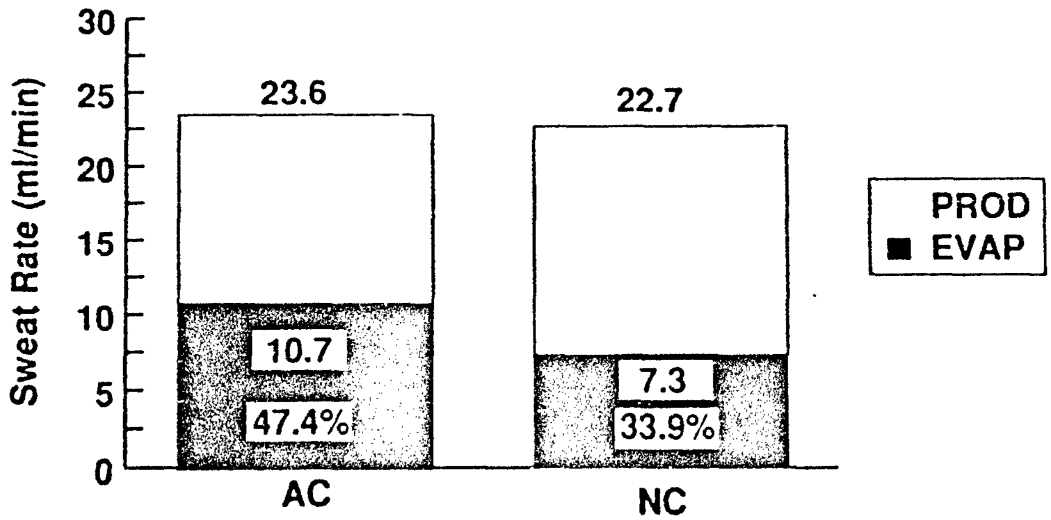


Figure 11i. Sweat production and evaporation rates during continuous work. AC = Ambient Air Cooling; NC = No Cooling.

In summary, all cooling scenarios (AC, IC, CC) decreased thermal strain compared to no cooling trials. Significant differences between continuous cooling and intermittent cooling were observed in the following measures: skin temperature, heat storage, and sweat evaporation efficiency. These investigators suggested that the 8.5-pound load experienced by subjects carrying the ambient air cooling unit during work periods might have counteracted some of the expected physiological and psychological benefits from ambient air cooling. Moreover, the filtered ambient air gained heat from the motor and control panel which increased inlet air temperature approximately 2-3°C. Therefore, it was suggested that skin temperature and the resulting thermal perception may also have been somewhat compromised. Interestingly, most subjects commented that air flow to the face was inadequate during work.

CONCLUSIONS

It has been the general scientific consensus to date that the concept of personal cooling systems shows some promise with regard to the problem of heat stress while wearing the CDE. However, most researchers agree that the ideal system has yet to be developed. Earlier commercially available systems have been shown operationally unsuitable for the USAF. The cooling systems developed by the USAF have been an improvement over previous apparatus tested, but are still less than ideal. Several distinct shortcomings still exist with the systems described in this report. For example, all of the self-contained systems would have limited cooling power which should prove insufficient under highly stressful conditions. The rationale for this projection is that the number of metabolic calories of heat generated during heavy work may be approximately double the estimated maximum removal rate of the backpack systems. Other sources of heat removal, i.e., evaporation, may not be able to make up this difference and might contribute very little when the environmental conditions are harsh (i.e., very high humidity). This projection assumes a 100% efficiency of the systems. Furthermore, the maximal sustained capability of the cooling garment (vest) has not yet been fully determined; this may be a highly limiting factor in and of itself, regardless of the cooling power of the chiller unit. Most likely a vest-size garment will be able to remove only a percentage of the metabolic heat load. On the other hand, it is important to remember that a significant amount of cooling appears to be within the present technologic capabilities, which could be of some help for selected operational scenarios.

Complicating this personal cooling problem is the issue of the logistical support arising with the deployment of any system. This latter concern stems from the frustration experienced during testing by both the development personnel and the using commands. This is not a simple problem. Overall, the reliability of any of these systems is unproven; however, some of the components employed have already been used commercially. The ice pack is obviously the least complex, but the feasibility of continuously refreezing these units in the field has been questioned. This latter consideration seriously complicates utilitarian aspects of an ice sink. Therefore, supporting any of these backpack systems in the field may prove to be a logistical nightmare. Obviously it is important to avoid developing a system that may work in a laboratory environment, but could not be logistically supported in the field.

In conclusion, the USAF approaches to the thermal stress problem due to the CDE wear have been presented. This is a complex problem and no ideal system has been identified. Nevertheless, some significant amounts of externally supplied cooling are probably within prototype capability with the current technology. Limited deployment of certain systems might be the most attractive option for the near future. Thus far, the intermittent cooling approach, along with ambient air chillers, has shown the greatest promise in the near-term for many USAF applications.

BIBLIOGRAPHY

Study #1 - Frye, A.J. and C.A. Flick. Report of Chamber Evaluation of Ground Crew Liquid Cooling System. Tech Memo (27220009 and 27290404), 18 Aug 1983.

Study #2 - Terrian, D.M. and S.A. Nunneley. A Laboratory Comparison of Portable Cooling Systems for Workers Exposed to Two Levels of Heat Stress. USAFSAM-TR-83-14, July 1983.

Study #3 - Carpenter, A.J. and C.A. Flick. Report on Liquid Cooling Development. Tech Memo 27290404, 4 May 1984.

Study #4 - Terrian, D.M. and D.J. Atwood. An Evaluation of Measures For Improving Military Effectiveness in a Chemical Defense Posture (Preprint) pp 243-244.

Study #5 - De Cristofano, B.S., J.S. Cohen, B.S. Cadarette and A.L. Allen. An evaluation of Commercial Microclimate Cooling Systems. Tech Report NATICK/TR-88/009L, 1987.

Study #6 - Constable, S.H., P.A. Bishop, S.A. Nunneley and T. Chen. Intermittent Microclimate Cooling During Rest Increases Work Capacity and Reduces Heat Stress. Ergonomics (In Press).

Study #7 - Bishop, P.A., S.A. Nunneley, J.R. Garza and S.H. Constable. Comparisons of Air vs Liquid Microenvironmental Cooling for Persons Performing Work While Wearing Protective Clothing. Trends in Ergonomics/Human Factors V. E. F. Aghazadeh, Ed. Elsevier, Amsterdam. pp 433-440, 1988.

Study #8 - Bishop, P.A., S.A. Nunneley and S.H. Constable. Comparisons of Air and Liquid Personal Cooling for Intermittent Heavy Work in Moderate Temperatures. Amer. Indust. Hygiene Assoc. J. 52(9):393-397, 1991.

Study #9 - Bomar, J.B., R.M. Shaffstall and D.M. Terrian. Evaluation of Chemical Defense Compressed Air Cooling Suits. Final Report. USAFSAM, 16 Sep 1981.

Study #10 - Bomalaski, S.H., Y.T. Chen and S.H. Constable. The Efficacy of Combined Approaches to Microclimate Cooling With Protective Clothing. AL TR- (In Preparation), 1993.

Study #11 - Chen, Y.T., S.H. Bomalaski and S.H. Constable. A Lightweight Ambient Air Cooling Unit For Use in Hazardous Environments. AL TR- (In Preparation), 1993.

SUPPORTING REFERENCES

Constable, S.H. Alleviation of Thermal Stress in Ground Crew Supporting Air Operations During a Chemical Warfare Scenario. NATO AGARD Proc. CP No. 457: 24/1-24/10, 1990.

Nunneley, S.A. and S.H. Constable. Intermittent Microclimate Cooling and Other Strategies for Relief From Work-Heat-Clothing Combinations. Trends in Ergonomics/ Human Factors IV. E. S.S. Asfour, Ed., Elsevier, Amsterdam, pp 391-395, 1987.

Bomalaski, S.H., T.Chen and S.H. Constable. Combinations of Microclimate Air Cooling During Work in the Chemical Defense Ensemble Decrease Thermal Strain and Increase Work Performance. Proc. Medical Defense Bioscience Rev. pp 877-880, 1989.

ADDENDUM

It should be noted that evidence was located concerning two other Air Force research efforts in this area. However, because of a lack of information regarding this work, they have not been formally included in this report. They are listed below.

Author Unknown "Liquid Cooling Vest Usefulness with Chemical Defense Garb." VNE Draft TR, Jun 82.

Myhre, L.G., IMP "Follow-on Heat Stress Testing," Trip Report 8-9 Mar 1984.